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STUDY & MODIFICATION OF CONVECTIVE STORMS

Report No. 4B
Contract No. DA 36-039 SC-89066

Order No. 265-62, Project Code No. 8900
Dept. of the Army Project 3A99-27-005-06

Final Report Covering the Period
April 1, 1963 - March 31, 1964

U.S. Army Electronic Research & Development Laboratory

Fort Monmouth, New Jersey

Study and Modification of Convective Storms

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Final Report, covering the period April 1, 1963 to March 31, 1964

Object of the Research: To obtain a quantitative understanding of the physical mechanisms involved in convective storms (nucleation, hydrometeor development, electrification, cloud and storm dynamics), both for natural storms and storms which have been artificially modified.

This report prepared by: Dr. P.B. MacCready, Jr.
Dr. T.B. Smith
Mr. C.J. Todd
Mr. A. Weinstein

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PURPOSE

This basic research program is directed toward obtaining a quantitative and qualitative understanding of the physical mechanisms involved in natural and modified convective storms. The various phases of the convective phenomena are considered from a balanced, integrated viewpoint. The aim is to investigate and understand critical factors such as: nucleation, hydrometeor development, electrification, cloud dynamics, environmental effects, and the complex interrelations between all these separate items. The research technique is built around the concept of an outdoor cloud laboratory, treating the clouds and storms in the simplest possible real situations. Seeding is used as a diagnostic research tool to permit observations of direct and secondary effects on hydrometeor development, electrification, and cloud dynamics.

The success of this type of study depends strongly on the adequate instrumentation of the complex cloud laboratory. Therefore this program necessarily entails the development of new or improved devices for making measurements, and just as important, also involves the development of the operational techniques for using the devices and handling the voluminous data generated.

Thus the program goal has had two interrelated parts: to obtain a proper understanding of the dominant physical mechanisms in the convective storms studied, and to advance the outdoor-laboratory techniques to the point where the techniques are capable of helping to obtain this understanding.

The first year of this two-year program involved technique development and preliminary analysis of dominant physical factors. This second, final year has involved some continuation of the measurement technique, has brought some of the research results to a more complete stage, and has, inevitably, uncovered some additional questions.

ABSTRACT

The final report describes research results from the second and final summer field season under the contract. The work consists of the continued development of field research and analysis techniques and analyses in a basic research program of cloud physics, cloud dynamics, and cloud modification for convective clouds at Flagstaff, Arizona. The report describes the field research system and data handling methods, for items not already described in the report[1] of the previous year. The report also includes evaluation of some of the 1963 season data and amplification of the results from the 1962 program[1,2].

During the field program the sub-cloud layer and representative cumulus clouds of all sizes were probed and studied using a coordinated system of an instrumented, supercharged, twin-engined aircraft, ground radars for tracking and meteorological studies, and a ground network of cameras and other instruments. Seeding was performed from a second aircraft, primarily the release of silver iodide particles from either a continuous burner or pyrotechnic Alecto devices. The observations were coordinated with those of USAERDL, which was performing a related study emphasizing condensation nuclei, IR, and electrification factors.

The primary new results are as follows:

1. The existence of a convective mountain wake phenomenon was further substantiated and analyzed in terms of the physical factors causing it. The air flow waves and distortions over the isolated peaks are found to exhibit categories based on wind speed analogous to those found elsewhere for two-dimensional ridges. The convective wake, a persistent upcurrent and radar echo region which often appears

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[1] MacCready, P. B., Jr., T. B. Smith, C. J. Todd, C. W. Chien, and Betsy Woodward, 1963: Study and Modification of Convective Storms, Final Report to U.S. Army Electronic R&D Laboratory, by MRI, Contract DA 36-039 SC-89066. AD 415 347.

[2] MacCready, P. B., Jr., T. B. Smith, C. J. Todd, 1964: Flagstaff Cumulus Studies, joint report by Atmospheric Research Group to the Atmospheric Sciences Section of the National Science Foundation, Grants No. G8334 and G11969, and by MRI to USAERDL, Final Report, Part A, Study and Modification of Convective Storms, Contract DA 36-039 SC-89066.

well downwind of the peaks, is shown to be primarily an interaction of the wake of the mountain and the source of buoyant air, and not to be linked particularly with the standing waves over the mountain. The convective region tends to move further downwind as the wind speed increases. The existence of radar echoes in the wake is shown to relate logically to the water available. The convective wake represents a persistent, forecastable major convective system which offers a great potential for controlled seeding experiments on large convective clouds.

2. The use of the continuous particle sampler data was greatly improved for (a) giving quantitative information as to complete droplet concentration size spectra by incorporating corrections derived for replica distortion and collection efficiency, and (b) giving some information on the presence of large droplets, to 1 mm diameter. In a study of the evolution of droplet spectra in a parcel rising up through cloud base, for both a warm (base + 7.5C) and cold (base -9.5C) case, the coalescence manifested itself to reduce droplet concentrations quickly, in contradiction to assumptions in the 1962 season. The observed rapid coalescence of droplets even smaller than 10 μ diameter is not a consequence of classical theoretical studies of coalescence, and seems too great even to obtain just because of altitude effects; small electrification factors are suggested as permitting the effect.

3. In a warm base (+7.5C) situation giant droplets were found entering the cloud base and growing into 1/2 and 1 mm drops. By -6C in a strong updraft some of these rising drops were found to be frozen. In a cold base situation (-9.5C) no giant droplets were found.

4. A particular cloud seeding case study is presented, in which the seeding plane, observation plane, and expanding seeded echo are monitored by radar, the seeded cloud is observed photographically, and the seeded cell (entirely glaciated) and unseeded cells are penetrated by the research aircraft measuring droplet and crystal populations.

5. Qualitative results of cloud seeding for the 1962 and 1963 seasons are reviewed, including glaciation, radar echoes, precipitation, and buoyancy and dynamic effects. Quantitative factors are considered for seeding with particles released from an airplane, and the results compared to the sort of effects observed. The rate of expansion of the plume is derived, and the concentration of nuclei versus time and radius presented. For the short time intervals usually involved, typical aircraft seeding is found to tend to produce rather small seeded

volumes having strong overseeding. Crystals growing in non-overseeded volumes can have their growth inhibited as more crystals are mixed into the volume, from turbulent mixing as the overseeded volume expands, and also as more nuclei become active in the rising, cooling parcel. For maximum seeding effects from an aircraft, the slowness of natural dilution processes often require that the material be released impractically early in the volume in question. Typical seeding with dry ice is found to be able to generate locally higher crystal concentrations than even intensive overseeding with silver iodide.

6. A short series of penetrations in the upper portions of large non-precipitating convective cells showed outflow velocities comparable to the core vertical velocity.

7. In flights ranging as high as 9000 feet above cloud base, undiluted cores were often encountered, the cores having horizontal dimensions on the order of a kilometer.

8. Strong radar angels appeared regularly on the 10 cm M-33 PPI scope and were studied briefly. Their presence correlated well with warm temperatures and other factors favoring thermal formation, and dry air. Some moved with the wind and were presumably related to thermals. Aircraft traverses through the echoes showed upcurrents and potential temperature excesses of 0.4 to 0.8C. Some moved unrelated to the wind, and even straight upwind, and must represent a distinctly different type, with the cause as yet unknown.

PUBLICATIONS, LECTURES, REPORTS, & CONFERENCES

Papers and reports pertaining to this work have been thoroughly reviewed in Part A of this final report.

A paper by T. B. Smith and A. Weinstein, "Flow Patterns and Convective Precipitation in the Wake of an Isolated Peak", was prepared under this contract and, with revisions, is intended for submission to a journal. It draws somewhat on previous NSF-cosponsored work, reported in Part A of this final report, but is considered primarily as an output of the USAERDL sponsorship. It constitutes Chapter E of this report.

Interim Report No. 2, "Study and Modification of Convective Storms", 1 April 1963 to 30 June 1963, was submitted to USAERDL at the start of the summer, 1963. This report reviewed preparations for the 1963 field season and summarized the operations plans for the work at Flagstaff.

Dr. Helmut Weickmann, USAERDL, visited MRI on 16 March 1964 to discuss the analysis and final report for this program.

At Flagstaff during July and August there were regular semi-formal meetings attended by all interested members of USAERDL, MRI, Schaefer's students, and visitors. All meetings were held at the conference room of the Research Center of the Museum of Northern Arizona. At most meetings there was a combination of coordination, project business, and technical or general interest talks by investigators and visitors. The participants included:

P. B. MacCready, C. J. Todd, T. B. Smith, A. Proudfit, E. Woodward, MRI

H. Weickmann, H. Kasemir, USAERDL

V. J. Schaefer and Students, New York State University

L. G. Davis, Pennsylvania State College

A. Goetz, California Institute of Technology

O. Berg, Aerojet-General

B. McLean, AMS

A. Sims, Illinois State Water Survey

J. Donnon, NOTS, China Lake

P. Sorenson, USWB, Flagstaff

DISCUSSION

A. Introduction

This report summarizes MRI activities relating to the second, final summer field season of USAERDL support of the investigation of convective clouds and storms at Flagstaff. This report does not duplicate material of the final report of the work the first year[1] or the joint final report by MRI to USAERDL and ARG to NSF covering all the field seasons prior to 1963[2] except for a small amount where required for clarity, continuity, and to make each report self-sufficient. The first year of this two-year program emphasized instrument development and field research techniques, and included research results pertaining to cell dynamics, mountain flows, atmospheric electricity, and quantitative in-cloud seeding effects. During the second year more advanced instrumentation was utilized, some instrument development continued, and the research results advanced appropriately.

The field phase the second year required more time and expense in the field than had been planned, primarily due to the difficulties with the more complex apparatus involved and the loss of efficiency necessitated by the late start of the preparation period, and as a result the analysis phase has been smaller than optimum. The data warrant more complete analyses than can be presented at this time, but the present evaluation does include significant advances. The cloud physics analyses thus emphasize the less complex situations, for these readily produce the most clear-cut results.

It has been necessary to divide this report into various sections so that the subjects could be presented with sufficient clarity. Since no one part of the report can be completely separated from the rest of the program, many of the MRI personnel have contributed to each part. The primary report responsibility for certain sections lies as follows:

Instrumentation (Chapters C, D): P.B. MacCready, Jr.
The Convective Wake (Chapter E): T.B. Smith and A.I. Weinstein
Radar Angels (Chapter F): A.I. Weinstein
Undiluted Cores (Chapter G): C.J. Todd

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[1] Ibid.

[2] Ibid.

Droplet Concentrations (Chapter H): C. J. Todd
Concentrations, Drop Growth, and Freezing (Chapter I):
P. B. MacCready, Jr.
Cloud Lateral Velocities (Chapter J): P. B. MacCready, Jr.
Seeding Case (Chapter K): P. B. MacCready, Jr.
Quantitative Seeding Concepts (Chapter L): P. B. MacCready, Jr.

All other report sections are considered as the responsibility of the general MRI staff. It should be emphasized that the main technical results have depended almost completely on the development of new equipment and the use of these new devices and standard devices under trying field conditions. The project results are therefore in large measure the outcome of the efforts of those who participated at Flagstaff and who are listed later in this report under "Personnel". Special mention should go to Mr. J. Gretta, Mr. A. Proudfit, and Miss E. Woodward who worked on the aircraft operations and instrumentation at Flagstaff, and to Mr. F. Clark who assumed responsibility for the radar. Mr. K.M. Beesmer and Mr. D. Smith assumed the data handling responsibility at Flagstaff and the data sorting and preparation later at Pasadena.

B. Objective and Scope

The over-all aim of the cumulus studies at Flagstaff is to gain a physical understanding of the microphysics and dynamics of convective storms, both natural and artificially modified. As far as possible the physical understanding should be advanced to yield a quantitative picture of the interrelationship of dominant factors. One long range aim of such work is the eventual modification of such clouds for practical purposes. Cloud seeding is being used now as a research tool; the eventual practical utilization must be built on the framework of adequate physical understanding bolstered by the sort of quantitative data which can make modification a true engineering science.

The present Flagstaff studies form a link in the long chain of cloud investigations there by MRI and the affiliated Atmospheric Research Group. The program philosophy has always followed the plan of obtaining a physical understanding of dominant mechanisms. In the first years only small clouds were studied. As techniques, understanding, and resources grew, it was possible to study the larger, more complex clouds profitably. The program accent has now evolved more toward studying the cloud dynamics, while still simultaneously considering the more specialized subjects emphasized in previous years.

Flagstaff is considered as an outdoor cloud laboratory. The isolated San Francisco Peaks form an orographic and heat source feature which helps emphasize certain meteorological factors and also helps concentrate repeatable cloud developments in one spot where they can be intensively studied. The numerous complex variables cannot be duplicated in proper interrelationship in a confined laboratory. Thus the laboratory gear is brought to Flagstaff. The apparatus required is extensive because no potentially-dominant factor can be ignored.

This report is the equivalent of various separate but interrelated reports. Each section treats a complete subject. Each section, of course, has appropriate conclusions given in its text. One section, Chapter E concerning the convective wake, includes a separate summary; the conclusions for this and the other sections are contained in the Abstract and Over-All Conclusions of the whole report.

Practical limitations as to the scope of this report have prevented inclusion of a section on electrification (although electrification instrumentation is presented) and a section on detailed case studies of the seeding studies (a summary is given, plus details for the July 29 case). The field data from 1963 for both these subjects were rather good.

The over-all two-year USAERDL-sponsored program, represented by this final report (Part B), the joint final report (Part A) with MRI-USAERDL and NSF-ARG, and the final report on the 1962 season, has fulfilled the goals of developing and demonstrating outdoor-laboratory research techniques and of advancing the physical understanding of interrelated factors of nuclei (condensation and freezing), droplet and hydrometeor development, electrification, and cloud dynamics, for natural and modified clouds. In some subjects, the work has uncovered new concepts, in other subjects it has agreed with classical theory and provided quantitative information to make the theory more usable. Certain avenues of specialized research are suggested by the present results, but the program also emphasizes the continuing need for studies which deal with the interrelationships of several disciplines.

C. Instrumentation and Data Handling

General

The instrumentation, field research techniques, and main data handling methods have previously been described in the final report for the 1962 field season, and further details are given in Part A of the subsequent final report. Only those items which are significantly different will be included here. The 1963 data system proved appropriate for the designed task, as will be evident from the results sections. The system principles are thus properly developed, but of course there can be continual improvement in the details of individual measurements and data reduction.

The 1963 program represented the fifth year of a slowly expanding field research project at Flagstaff. The field system was the most advanced as far as measurements and results are concerned, but as with the project every year, the field work was difficult and many new problems continually had to be overcome. The good features and the problems are given here. The main problem is that associated with the first field use of any new piece of apparatus -- a problem which always arises in any rapidly advancing research program, but which is made particularly severe when there is insufficient time from the start of the project preparation until the period of the correct weather conditions. The main project changes from 1962 were the use of the M-33 radar for tracking and the use of a single heavily-instrumented plane for the research flights instead of two less-heavily-instrumented ones.

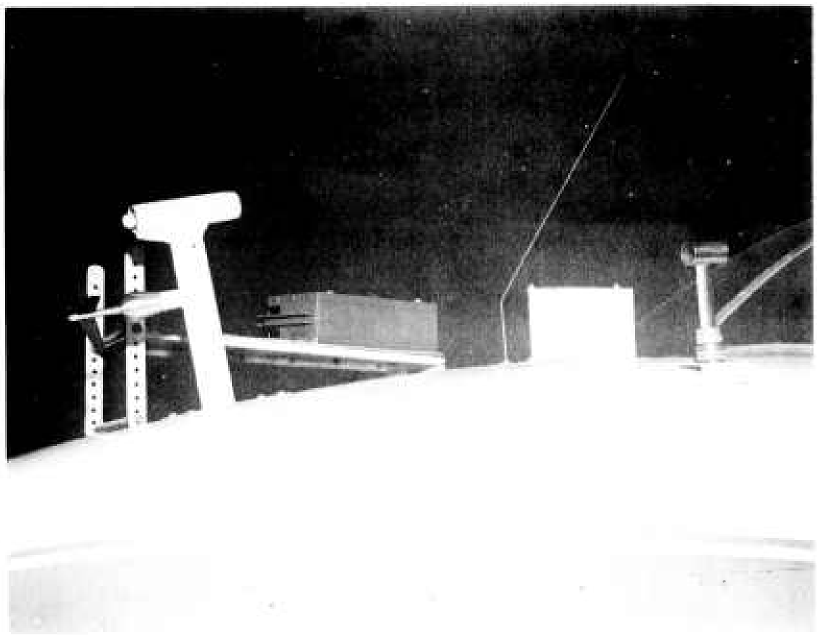
The airborne continuous particle sampler is described separately in this report in Chapter D.

Aircraft Operations

The 1963 field program was centered around the use of a Cessna 180 single-engine airplane for silver iodide seeding and a supercharged Piper Apache (see Fig. C-1) as the instrumented research aircraft.

The Cessna, referred to as M-2 during the project, had two Fuquay-type acetone burning silver iodide generators hung from bomb racks under the wing. The generators operated reliably. As an alternative seeding method, Alecto pyrotechnic units were sometimes used. These were provided by the Naval Ordnance Test Station, China Lake, California, through the cooperation of Mr. Jack Donnan and Dr. Pierre St. Amand.

a. Supercharged Piper Apache. The potential gradient probes can be seen above and below the fuselage. Sampler not yet installed at nose.



b. [illegible]

Fig. C-1. THE RESEARCH AIRCRAFT.

NOTS also provided a rack which permitted six Alectos to be hung from the bomb shackles under one wing. The Alectos were set off in sequence as desired from a switch in the cockpit. About twelve Alectos were fired during the project; another eight failed to fire, presumably because the igniter portion had to be packed hurriedly to meet the deadline on the project. The Alecto generator consumes about 2.6 pounds of silver iodate in 45 seconds.

The effective output of the acetone type and pyrotechnic type generators is discussed in Chapter L. It had been hoped that the relative outputs could have been ascertained, at least roughly, by particle sampler crystal counts in seeded clouds. However, as pointed out in Chapter L, the number of crystals observed in overseeded areas may depend on the number present when glaciation is first complete, and so valid comparisons are hard to make except in the case where the diffusion of particles is great enough to prevent complete glaciation locally. On July 30, 1963, as a comparison, one Alecto unit was fired and later the acetone generator was turned on for 15 minutes under some shallow (2000 ft thick, -8C to -12C) clouds. In each case the immediate cloud area glaciated thoroughly and in about 40 minutes virga had descended several thousand feet below cloud base. Qualitatively the effects appeared rather comparable, and they suggested that there was not a gross difference in total output from the two seedings but perhaps a slight advantage with the Alecto. This constituted a very crude comparison, but was of some value near the start of the 1963 seeding program in providing hints for planning subsequent operations.

The Apache altitude operation, as loaded and with the research probes mounted, proved to be marginal in spite of the superchargers. It is now felt that the 160 hp version, rather than the 150 hp version used, would have proven to be considerably better for the required flights (a more heavily loaded 160 hp supercharged Apache had previously been checked satisfactorily to 28,000 feet). Climbout from the 7000-ft field was uncomfortably slow. The maximum altitudes used were just above 23,000 feet true altitude. The aircraft power was sufficient for higher climb, but the fuel pressure would drop off too much, presumably due to the relatively warm temperature permitting vapor lock in the unpressurized fuel system. In icing clouds, after a short time the power would drop way off as though from icing over of the air intake. This phenomenon was not encountered in similar supercharger installations, and the cause is still not known in spite of various tests made during the summer. The flight operations were adapted to these particular aircraft limitations; for example, at high altitudes the climbs were made outside of clouds. The Apache did turn out to be a good research aircraft from the standpoint

of cockpit space and general maneuverability and slow speed flight characteristics. Spirals in upcurrent cores did work properly.

Both aircraft were operated inside rough thunderstorms with lightning, moderate hail, and strong turbulence. The flights are considered perfectly safe because of the slow flight speeds used.

Aircraft Instrumentation

The data system in the Apache was an adaptation of the items already covered in the 1962 report, including the communications system, magnetic tape recorder, continuous particle sampler, and Brush recorder with associated modules. A 16 mm time-lapse camera was added, pointing forward, taking one picture per second. The Apache was equipped with a 125-ampere, 24-volt alternator on the left engine, and a converter giving 1 kw of 110 v 60 cycle power. In 1963, a 6-channel Brush recorder was used, with various event markers showing time, special events, communications, camera frames, and sampler frames. Some of the variables were cycled so that more than six could be recorded simultaneously. Electronic problems with the cycling and subsequent interactions between modules kept the cycler from being used except at the beginning of the project. On any one flight six variables (with some shifting of variables during the flight) proved to be adequate, although more would be desirable. Sometimes in addition a 2-channel Brush recorder was added for special electrification measurements, conductivity or hydrometeor charge, and occasionally this recorder was used with a 12-volt converter for conductivity measurements in the Cessna.

Parameters recorded in the Apache were:

1. Altitude (light follower on altimeter)
2. Rate of climb (Crossfell variometer)
3. Temperature (thermistor in vortex housing, 8C overlapping scales)
4. Turbulence (MRI Universal Turbulence Indicator, ϵ indication)
5. True air speed (from the turbulence probe)
6. Mixing ratio (MRI phosphorous pentoxide electrolyzing device)
7. Liquid water content (Johnson-Williams hot wire)
8. Infrared (Barnes 8 - 12 μ band unit)
9. Compass heading (light follower on remote gyro-magnetic compass)
10. Potential gradient (radioactive probe, operational amplifier device)
11. Aircraft charge (other output from the potential gradient device)
12. Hydrometeor charge (open-ended Faraday cage, Kistler charge amplifier)
13. Conductivity (Gerdien tube method)
14. Hydrometeor size (capacitance method)

Items 10 through 14 are discussed further in this report; items 1 through 9 have already been treated in the previous reports.

Figure C-2 shows a typical Brush chart taken from a flight. The noise appearing on some channels is caused by radio transmissions; it was decreased considerably during the field project by different shielding and grounding.

The Atmospheric Electricity Measurements

Potential Gradient and Aircraft Charge

The 1963 measurements were made with the latest version of the radioactive probe technique employed in the previous summers. One probe is above the middle of the fuselage, and the other is below. The voltage difference between probes is a measure of the vertical potential gradient, and the average voltage of the probes relative to the aircraft is a measure of the aircraft charge.

The design for 1963 permitted the probes to be "balanced" in flight so that the aircraft charge (AC) would not appear on the potential gradient (PG) record, and vice versa. This was accomplished by having each probe in a separate amplifier circuit with the aircraft as ground. Adjustment of the gain of one amplifier in flight therefore permitted balance to be obtained. As desired, the aircraft would be charged negative by a corona point at the tail raised to +20, 000 volts. This would be done when the aircraft was flying in a weak or at least steady PG. Then the amplifier gain would be adjusted so the same PG was shown with the aircraft charged as with it uncharged.

Each electrometer has a CK 5886 electrometer tube input and a Philbrick P-65 solid state amplifier connected as an operational amplifier. The operational amplifier technique gives low output impedance which simplifies the summing and difference resistor network, gives great linearity to the amplifier so balance is maintained at all levels, and reduces time constant effects from capacitance of the input cable.

The probes each use 500 microcuries of Polonium 210, with a 137-day half-life. These α emitters are set at the ends of 10-inch rods which fasten into 6-inch long, 1-inch OD teflon rod insulators. The 10^{12} ohm dropping resistor is sealed inside the insulator with

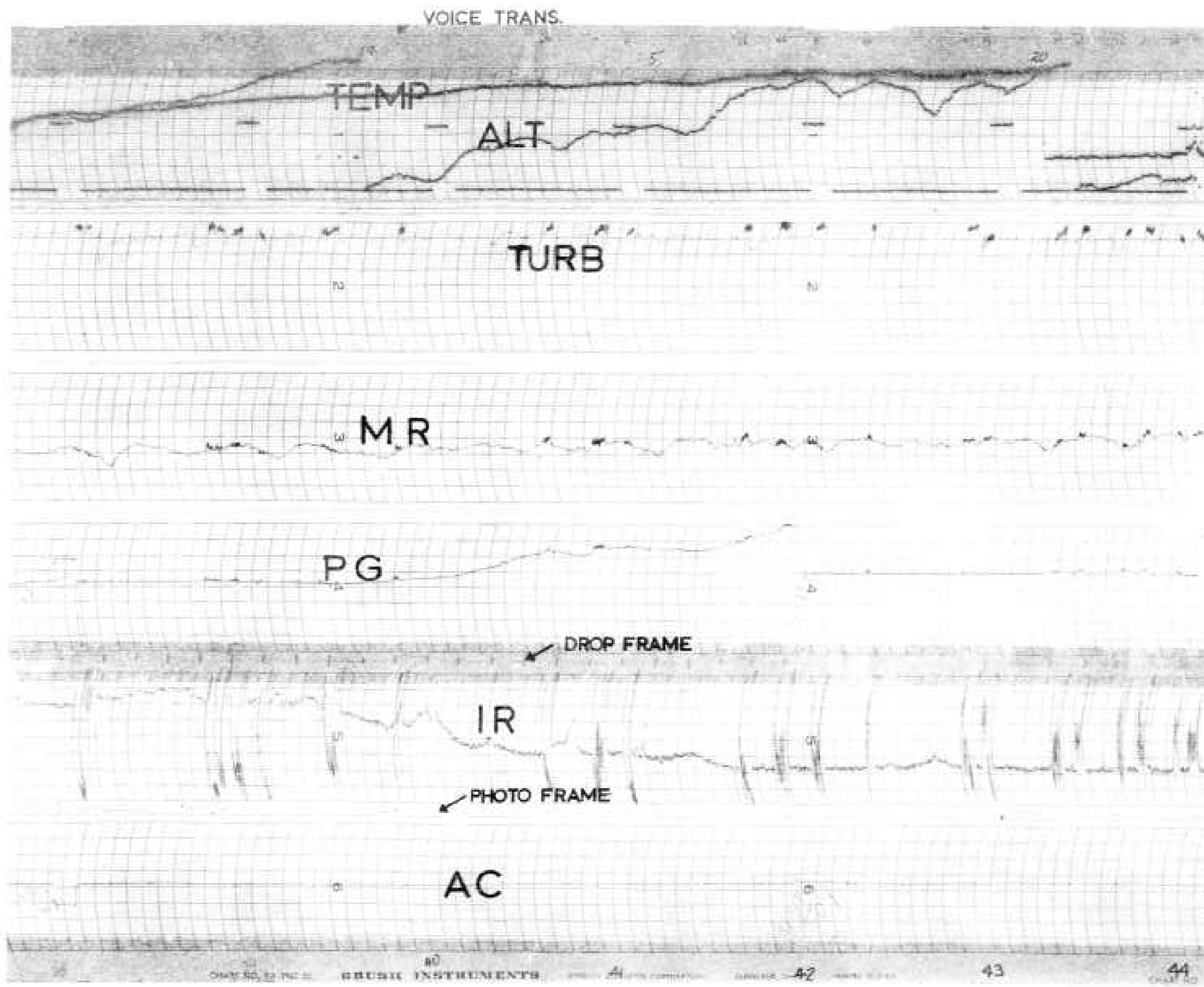


Fig. C-2. SAMPLE RECORD FROM 6-CHANNEL AIRBORNE RECORDER.

some silica gel to assure low humidity. A wind shield keeps large hydrometeors from directly striking the insulator, and the probes do work in icing conditions after some other sensors have iced up. The radioactivity emits α particles with a range of about 1 inch at sea level, ionizing the air in that volume. At high altitude the range is greater, inversely proportional to air density. The radioactive elements were on 3/4 x 3-inch flat metal containers, facing downward to avoid getting wet. For the greatest accuracy the PG system had to be slightly rebalanced at high altitude because the effective probe height became less on the upper probe and greater on the lower as the density was reduced. This effect can be eliminated in the future by using a stop-plate 1 inch below the radioactive element.

The 10^{12} ohm resistors have finite capacitance and this tends to introduce an extra time constant into the system response. By putting a short stub of wire inside the resistor connected to the cable end, a compensating capacitance could be obtained which served to give the whole system a very short time constant of about 1 millisecond. Lightning discharge details were apparently reliably shown to the frequency limit of the Brush recorder.

Conductivity

Plus and minus air conductivity was obtained satisfactorily on the ground and in the aircraft with a surplus vibrating reed unit manufactured by Applied Physics Laboratory. This is a sensitive electrometer connected to a Gerdien tube. The polarity is shifted by a bias battery. After the unit was completely de-moisturized it operated satisfactorily. No strong effect of air speed through the tube was apparent in the device as installed in the Cessna 180 and finally in the Apache, and doubling or halving the bias voltage gave linear output variations, showing that the operation was properly in the ohmic region.

In the Apache the tube was connected to the air intake at the front right side of the fuselage. The interconnecting tube was first rubber; this gave large variations with air speed and generally seemed unsuitable for unknown reasons. Then the plastic inter-connecting tube which had been used in the Cessna was tried, and worked perfectly as it had in the Cessna (connected to the air vent in the wing).

In the Apache when the aircraft was charged minus with the charging device used for balancing the PG unit, the indicated

negative conductivity would decrease greatly while the positive conductivity measurement would be virtually unaffected. This derives from the removal of fast negative ions by the gradient around the fuselage. The effect can be decreased by picking up the air further from any upwind aircraft structure.

Hydrometeor Charge

The same hydrometeor charge sensor was used in 1963 as in 1962, described in the 1962 season report and also by MacCready and Proudfit (1964). The charge is picked up as the charged hydrometeor passes through an open-ended Faraday cage mounted above the top of the nose of the Apache. In 1962 the 1-millisecond pulse generated from the Kistler charge amplifier circuit was slowed by addition of a longer time constant and then presented as a pulse on a Brush recorder running at high speed. In 1963 the pulse stretcher was eliminated, and the Brush calibrated for the short duration pulses (attenuation was only about 50 per cent). This technique speeded the response of the system and permitted more numerous counts before the zero bias level would be altered.

Hydrometeor Size

An experimental hydrometeor size sensor was prepared based on the capacitance effect as the hydrometeor passed through the parallel plates of a condenser. This was an airborne adaptation of the method used by Smith (1955) on the ground to establish the size of the same hydrometeors whose charge was measured just above by the Faraday cage method. When the raindrop is between the condenser plates, the capacitance is altered slightly, altering the tuning of an oscillator which includes the condenser in a resonant circuit. The frequency shift is then converted to an analog voltage, proportional to the drop mass. The simplicity of the device makes it attractive as an airborne hydrometeor sensor. The present unit covers masses for drops in the range of 1 mm to almost 1 cm diameter; a smaller unit could go down to 100 μ diameter. The airborne system (sensor shown in Fig. C-1) was built for MRI by Acoustica Associates, Inc. There was insufficient time at Flagstaff to do more than just verify that the unit would operate on the aircraft. Subsequently at Altadena a few laboratory tests were made which showed confusing results.

Laboratory calibration showed the device serves properly to give pulses proportional to drop mass. However, tests on the ground in a real rain showed spurious large pulses. Further brief laboratory trials implied that the splashing of drops causes the big incorrect readings. There has

has not been the occasion to pursue the matter much further. The unit is not microphonic; the insulated inner plate can be tapped with dry plastic without effect, but shows a large spike if the plastic is first dampened. There might be some effect of the drop charge, since drop charge as well as the change of the dielectric constant may alter the effective capacitance of the system and hence the output pulse. L. G. Smith (private communication) found no such trouble with his unit, but had a setup which decreased the possibility of splashing droplets entering the capacitor area, and used the device in conditions where drop charges were not large.

The simplicity of the technique makes further consideration worthwhile. A systematic laboratory investigation could quickly illuminate the good and bad features and show if further development would be warranted.

M-33 Radar

In 1963 an M-33 radar was used to substitute for one of the MR-4 radars employed in 1962. The M-33 consists of a 10 cm. acquisition PPI radar, and a 3 cm tracking radar which involves a computer and plotter and can present tracking data in reduced form. In the Flagstaff studies the tracking of the seeding and research aircraft is of great importance. This tracking has been done in the past with a GMD-1, which provides only angle and so causes data reduction complexity, and by pencil beam weather radars, which is a difficult and unreliable method even with an experienced radar operator. The M-33 thus constitutes a particularly useful tool for the aircraft tracking, and it also serves for tracking of zero-lift and sounding balloons.

The M-33 radar took a good bit of refurbishing and modifying to prepare it for the meteorological studies. The range and height readout was removed from the small board and fed into the range and height predicted board. The scales were changed to give 40, 000 yards and 80, 000 yards. The X-Y plotting board was modified to give two corresponding range scales, and was also altered to permit adjustable offset information. The time mark generator was modified to give 1/2, 1, or 2 minute dots or a solid trace with barb time marks. The height output was altered in scale to give height in feet on a scale consistent with other project scales, and was given an adjustable offset so height could be presented as mean-sea-level. The time base moving chart was also used for range, permitting radial speed calculations. Another output was assembled giving an analog voltage for ground speed from radial and azimuth speeds; this was recorded on a separate Esterline-Angus chart, and is discussed in Chapter J. The fan beam acquisition set antenna

was altered by changing vane orientation to give a more desirable pattern. 16 mm cameras were put on two scopes for the 10 cm set, and a third larger scope installed for direct plotting.

The M-33 worked well and reliably on the field project. Examples of its data are shown in Chapters F and K, and there is much information on balloon and chaff movements not yet analyzed. Mr. L. Davis, consultant from Pennsylvania State College, helped greatly with design modifications and with developing optimum utilization of the M-33 in the field. His report (M-33 Radar Modifications and Calibrations, Report No. 2, Grant #NSF-G24850, December 1963, Penn. State College) describes the sort of modifications mentioned above as well as others.

Data Handling

General

This project, which involves the instrumentation of the complex outdoor laboratory for the numerous factors dominating the development of clouds, particles, and electrification, necessarily produces great quantities of data. These data are generally of a type which do not lend themselves to routine digital processing. Each flight and cloud is treated as an individual case, and must be interpreted by professional personnel. The analyst tends to be most receptive to these types of data when they are put in the form of analog presentations. A data reduction and presentation scheme has been evolved to cope with these voluminous records. Its main principles have been presented in the previous final report, but there have been significant improvements since the 1963 field season and these will be discussed here. For data on the particle sampler data reduction see Chapter D of this report.

Data logging is a vital part of the data handling. It seems straightforward, but because of the complexity of the data it turns out to require careful attention. It has been found that cataloging and evaluating data immediately after they have been taken in the field is necessary to avoid near hopeless confusion in data reduction. This also helps find malfunctions in the equipment at the earliest possible time so that there is a minimum amount of data lost due to unknown equipment defects.

The type of data collected is as follows:

a. Aircraft observations
   6-channel Brush chart record
   2-channel Brush chart record
   Voice tape record from the observer
b. Airborne continuous cloud particle sampler
c. Ground based observations made by the M-33 and MR-4 radar
   16 mm film of the PPI scope
   Charts of the aircraft track
   Charts of the aircraft altitude
d. Film from nine 16 mm time-lapse cameras, both ground based and airborne
f. Miscellaneous observations, such as U.S. Weather Bureau rasonde
g. Army rasonde data
h. Hourly surface observations from the U.S. Weather Bureau Flagstaff Airport stations
i. Special surface observations taken by project personnel on and around the Peaks.

A running time-height diagram is kept up to date daily presenting as much of the data as possible. In addition, a rough descriptive summary of the day's events is made.

Flight Chart Reduction

The flight chart record data reduction system has evolved to an advanced stage. The data are converted with the aid of a special linear pantograph to a large chart, with the scales being altered and superimposed so that factors such as buoyancy and per cent of mixing of liquid water are easy to observe. The pantograph is pictured in the 1962 season report, and the type of scale presentation is given there and by Todd (1964a). Additional information and comments are put on the master chart as shown in Fig. C-3. Droplet information is obtained to the same scale as discussed in Chapter D, and added to the master chart.

Cloud and Radar Data

The cloud development around the San Francisco Peaks has been recorded by as many as eight 16 mm unattended time-lapse cameras, and the radar echoes recorded on PPI scopes by additional cameras. A goal of analysis has been to set up a system for analyzing these records simply with an accuracy comparable to the resolving power of the 16 mm film system. Because of the large amount of information

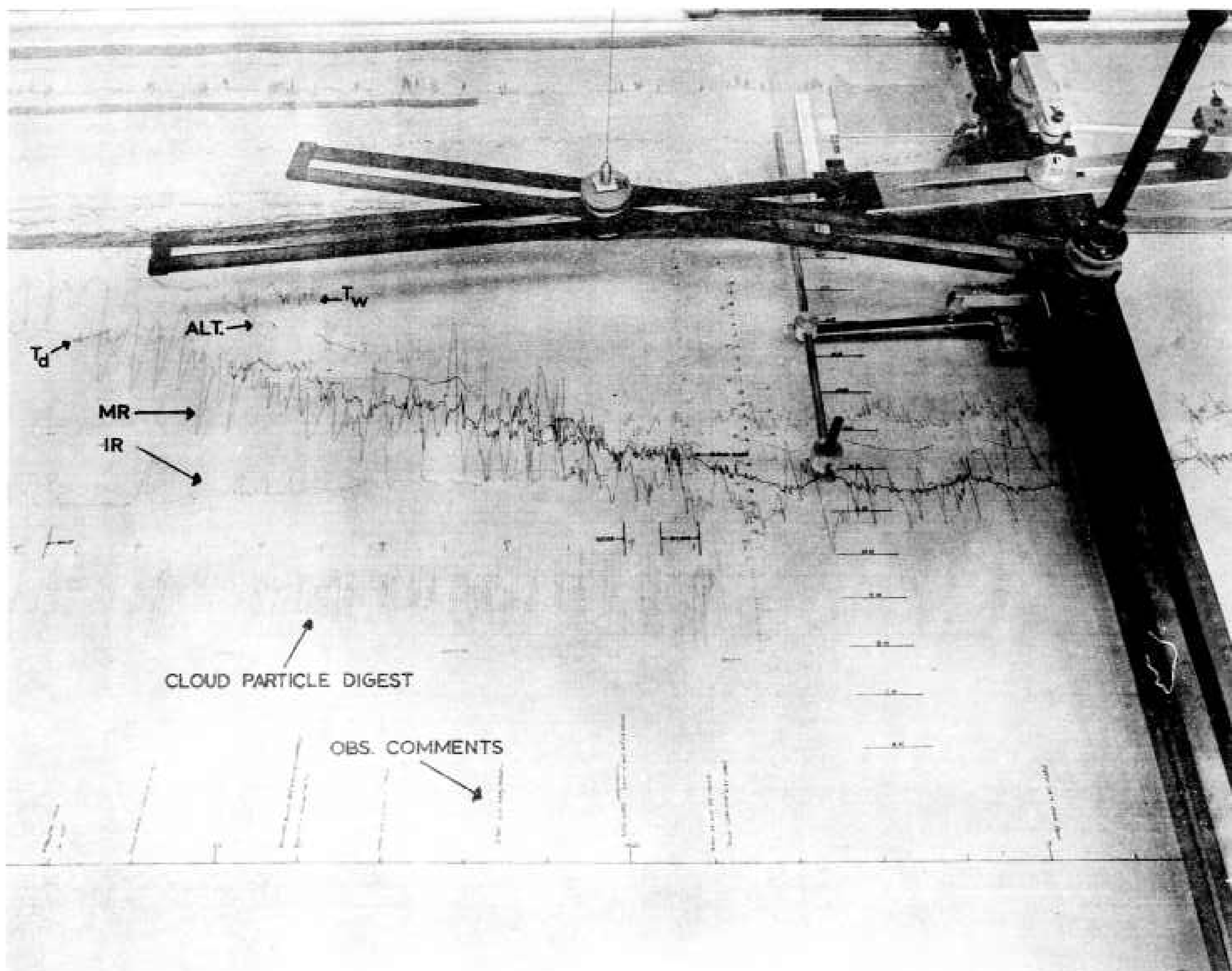


Fig. C-3. MASTER FLIGHT TIME SECTION.

carried on film, showing the cloud development from so many different places, it was necessary to present the different films so they could be compared with each other with the minimum of confusion, and allow the operator to concentrate on cloud development rather than geometry and lens corrections. The solution to this seemed to lie in developing a true scaled analog, by projecting each cloud film from the map location of the camera from which it was taken, with the image being on a small, movable, frosted plastic screen. If the screen were moved to the map location of the cloud being projected, it would be in true scale. If the projection lens system were the same as the photographic lens system, the same cloud could be viewed by projection from the map position of different camera locations. When these produced matched points on the movable screen, then the cloud location would be resolved beyond doubt.

There are several problems that have to be overcome for even a simple system. The first is that no 16 mm camera system was found that had compatible photographing and projecting lens systems. Therefore, projectors either had to be adapted to take photographic lenses, or cameras had to be converted to be projectors. The latter alternative was used; this was easier to do, but at the cost of losing fine focus of the camera. The second problem is that the projectors had to be properly located and have the freedom to be rotated for adjustment in two axes about the convergence points of the lenses. This requires carefully constructed special mounts.

When the projecting lenses are used to project only a few tens of centimeters and the focus is set for this distance, the diverging angle is different than if the focus is set for infinity. This can introduce a five per cent error in scale factors. It can be corrected by adding a correcting lens or by setting the focus to infinity and taking the actual measurements out of focus.

For a more advanced system, the projectors must be controlled from one central location so that they can be turned off and on and be operated in either stopped position or run forward or backward. It is easy to imagine such a system set up to operate with synchronized projectors, but this has not been done.

Figure C-4 shows the plotting table. The three lower projectors are the ones for the cloud movies, and so the height of their lenses represents the ground level for altitude measurements. The highest camera, at the left, projects the radar PPI film. The image reflects from two mirrors down onto the map, with the scale adjustable by moving the mirrors. This master map has the same scale as the plotting board on the M-33 radar.

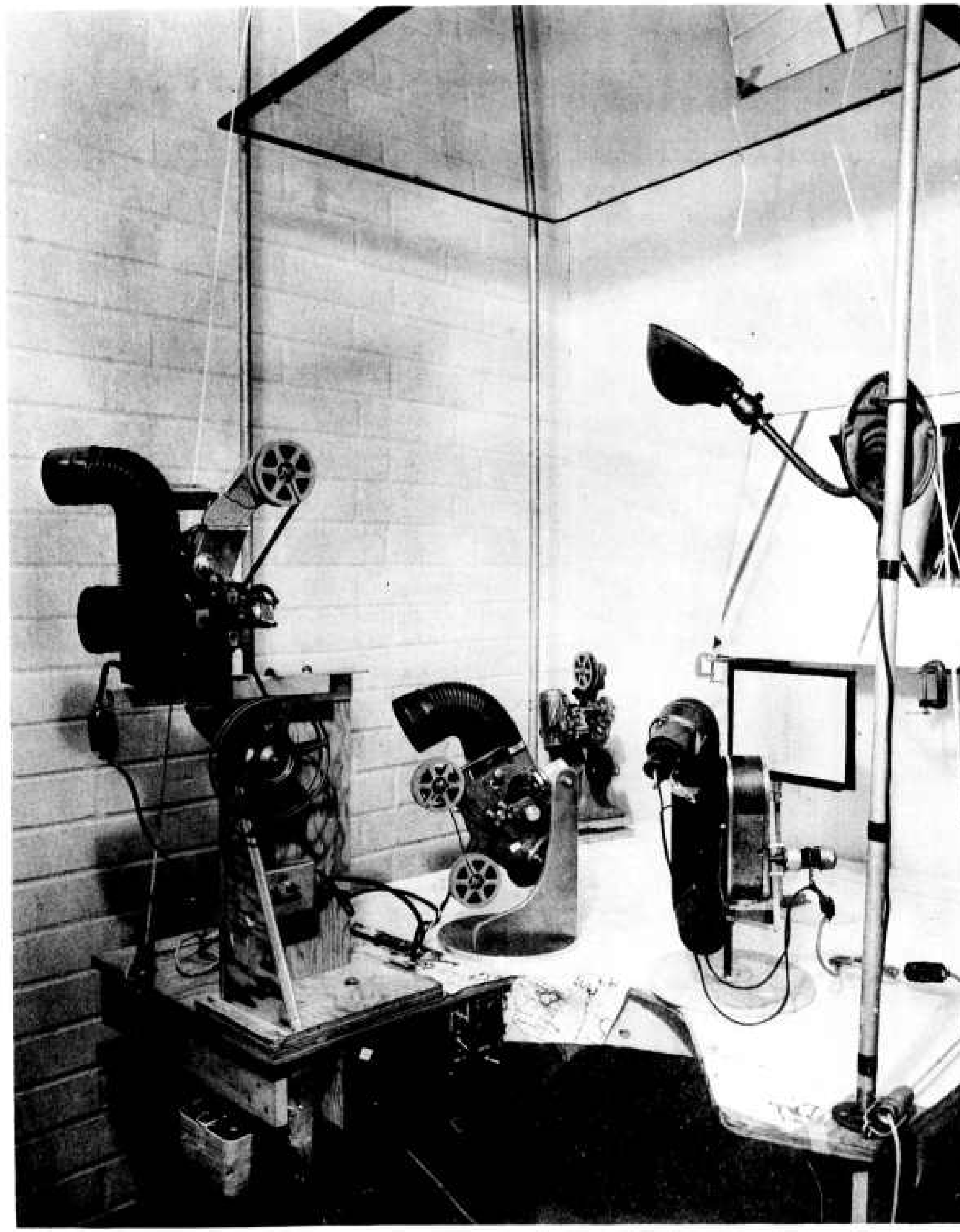


Fig. C-4. CLOUD PLAN POSITION MAP TABLE.

The radar data plotting has been regularly used on this project. The cloud photography phases of the system have been tested successfully to verify its usefulness but have not yet been applied routinely to data.

As a convenient way to visualize some of the data, plan position plots of the aircraft tracks and echo positions have been put on transparent acetate on the regular map scale. In many cases one sheet gives information for a 15-minute interval, but during critical phases of airplane probing or seeding an interval of just 3 minutes is sometimes desired. For convenience, these sheets are assembled into a folder in a manner which makes them spring out into three dimensions when the folder is opened. This is shown in Fig. C-5. This data presentation technique has proven to be extremely effective for a variety of purposes, including cloud growth plots and synoptic data, as well as the aircraft and echo tracks discussed here.

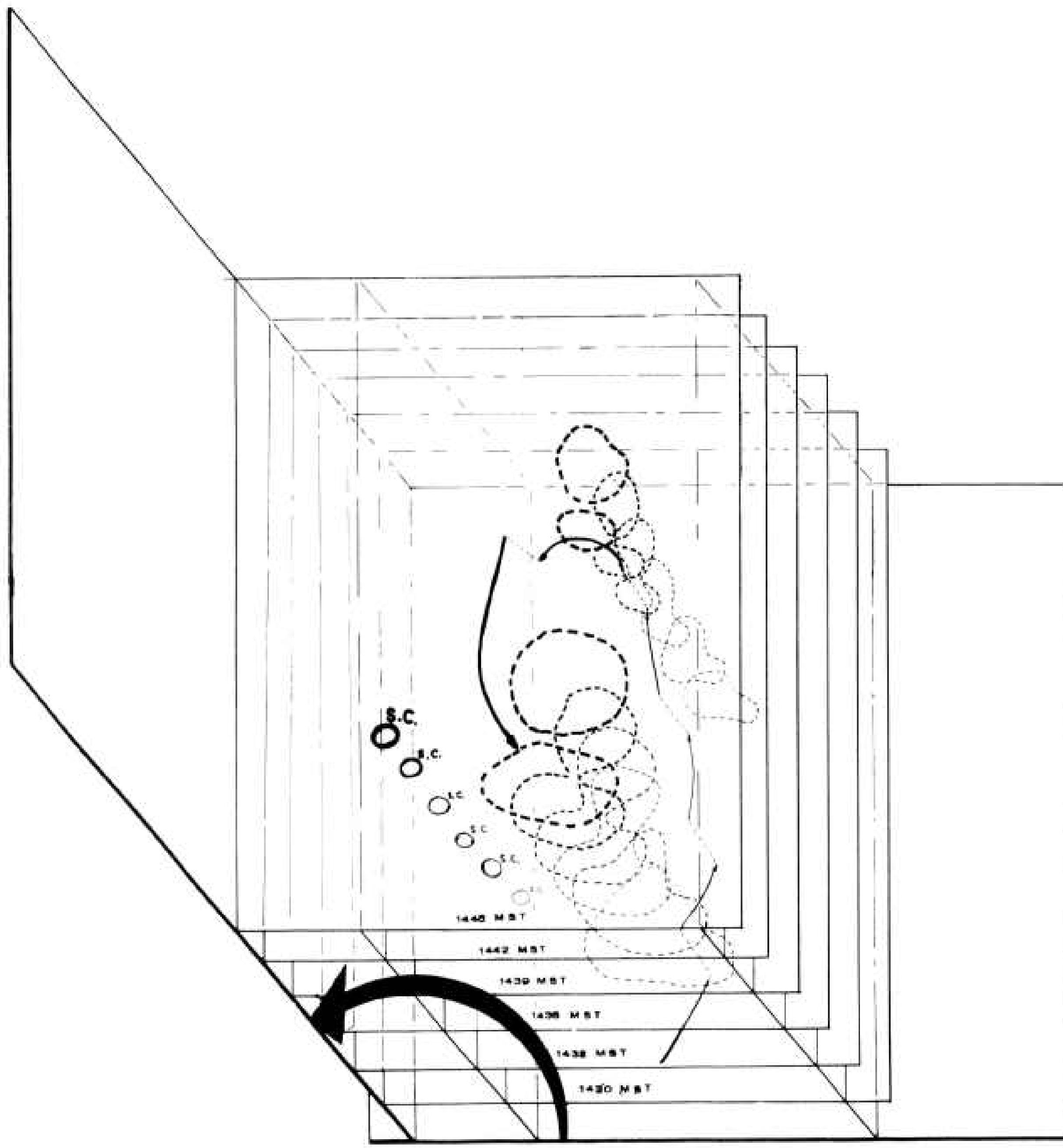


Fig. C-5. SHEETS STACKED IN FOLDER FOR THREE-DIMENSIONAL PRESENTATION.

Solid lines show the aircraft tracks and dotted lines the position of radar echoes (or clouds, if desired). S. C. refers to Sunset Crater.

D. The Continuous Particle Sampler

General

This vital instrument for these cloud physics studies has been described completely in the paper, "Continuous Particle Sampler" (MacCready and Todd, 1964), which was sponsored partially by the USAERDL project and by coexisting projects from NSF and NRL-ONR as well as by MRI internal research funds. Most of the initial formal development and calibration is attributable to the NSF and NRL-ONR sponsorship. However, the USAERDL project was the primary user of the device during the 1962 season, and the only user during 1963, and much of the practical development of the somewhat critical device therefore fell to the USAERDL project.

For completeness, the main features of the sampler will be mentioned here, extracted from the paper; in addition, features not covered in the paper will be described, and new information on the replication of large droplets cited. Some of the points and examples of the use of the instrument are contained in Chapters H, I, and K of this report, and examples have already been described in the 1962 season Final Report.

The 1963 sampler involved a different heating system for de-icing and to aid in the evaporating of the solvent, and a different solvent ventilating system, than had been used before. Many flight trials were conducted to establish the best adjustments and modifications. There are so many variables involved that a truly systematic development was impossible in the available time. By the end of the summer satisfactory compromises were established, and during the summer many usable records were obtained even when the operation was not ideal. The continuous sampler has proven to be a uniquely vital tool for cloud physics studies, and its further development and utilization are warranted.

Background and Principles of Operation

The continuous particle sampler was developed primarily to provide a method for ascertaining quantitatively the coexistence of ice crystals and supercooled water droplets in a cloud being seeded by natural or artificial freezing nuclei. It has turned out to handle this job particularly well, and also perform other valuable related tasks where particle size and concentration information is desired.

The device is a continuous version of the Formvar[1] method developed by Schaefer (1956) for making ice crystal replicas. Its main virtue is that it makes permanent replicas of the shapes of particles which impinge on a

[1] Trade name, Formvar 15-95E, Shawinigan Resins Corp., Springfield, Mass.

liquid-plastic surface. The Formvar plastic solution flows over the particle, completely enclosing it, and then the solution hardens as the solvent evaporates. The encapsulated particle may then evaporate or sublimate away, but its replica is preserved.

In the airborne continuous sampler, the liquid-plastic Formvar-solvent film is put on transparent 16 mm film which is continuously drawn past a slot exposed to the ambient air flow. The Formvar solution then hardens before the exposed portion reaches the take-up reel. Conceptually, the instrument is simple. However, the practical instrument requires that many design compromises be made to give proper coating, proper hardening, and good particle collection and replication.

The active development of this device began in 1961, when trials with various droplet collection methods showed that Schaefer's Formvar replication technique could lead toward an operational continuous sampler. An important factor in the development of the system has been the availability of a 16 mm film[2] which would not dissolve in the solvents used (chloroform or ethylene dichloride). This meant that 16 mm film handling methods could be adapted to the sampler, which was a great convenience for the drive mechanism as well as in the subsequent viewing of the replicas.

The first complete sampler system was used successfully in the summer of 1961 on the Atmospheric Research Group Flagstaff studies. In this dipper tank system the Formvar coating was precoated on the leader film, and then softened before exposure by running the film through a solvent bath maintained at a particular level by means of a float valve. System design and some results were presented by Todd (1961).

In the fall of 1961 the unit was taken to a droplet collector comparison conference in France organized by H. Dessens. A miniature wind tunnel, consisting of a tube and a blower, provided the air flow on the ground to substitute for the airplane motion. This device was operated satisfactorily in-cloud on a mountain peak, along with collector equipment of other investigators. The results were given by MacCready (1962b).

In the summer of 1962, two improved units were installed on two aircraft, one unit being the precoated film variety, the other using uncoated film and applying the Formvar-solvent mixture just before exposure by means of a coating wheel. Results of the device during the summer are given in the final report by MRI to USAERDL on the 1962 season. The case studied in most detail, a spiral up into a seeded cloud on 15 August 1962,

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[2] Cronar, P40A Leader, Polyester Photographic Film Base, duPont, Wilmington, Delaware.

has been analyzed more thoroughly by Todd (1964a) under sponsorship of both NSF and the present USAERDL program. Todd utilized the sampler data to derive the growth rate of crystals in the cloud at various temperatures and to verify the crystal concentrations resulting from the silver iodide seeding (see Chapter K).

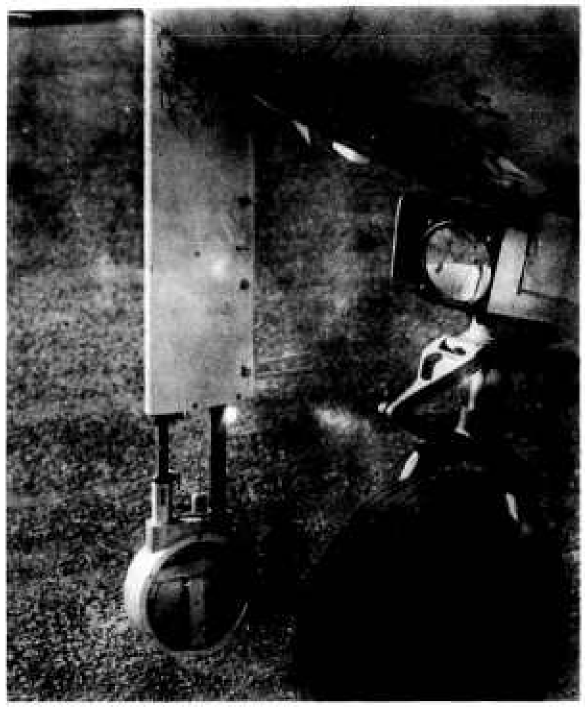
Of the two sampler methods used in 1962, the coating wheel method seemed the more practical (more controllable, and less likely to stick), and therefore an adaptation of it was created for the 1963 summer measurements. The unit is shown on the Apache aircraft in Fig. D-1. The collector part of the sampler was mounted on the nose of the Apache, well away from the fuselage where the air flow is relatively undisturbed. The drying tubes went back into the cockpit area where the supply and take-up reels were installed. A projector system was attached in the cockpit so the observer could watch the film samples in flight (the sampled material would reach the projector 70 seconds after the sampling), and adjust the heating controls to give proper replication as the flight progressed. Results from the sampler in 1963 are contained elsewhere in this report (Ch. H, I, K).

The final version of the sampler was built for the NRL-ONR project in the Fall of 1963, and is described by MacCready and Todd (1964).

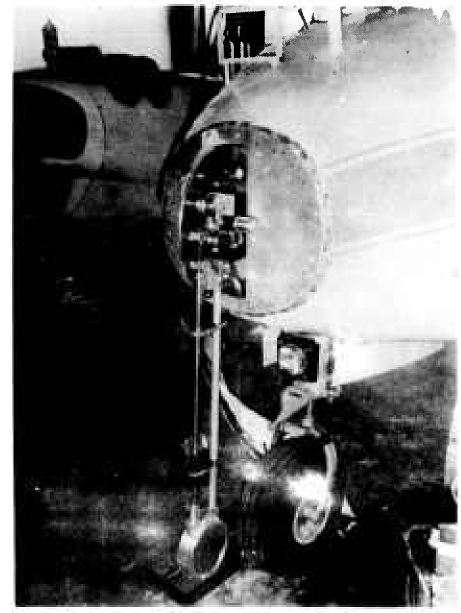
Design Factors and Compromises

The Formvar coating on the film must be soft during the impaction process and flow readily so as to encapsulate the particle, but still be stiff enough to resist being blown off by the wind, and stiff enough to keep the droplets from clumping together (here called flocculation). The coating hardens as the solvent evaporates. This hardening must not take place before the film passes the slot, but must occur before the film reaches the take-up reel and before the particle size or shape is significantly altered. The evaporation cools the film, and water from the ambient air can condense on the film (called blushing) or can cause spurious growth of ice crystals. This cooling effect can be eliminated by adding heat to the system, but excessive heat can melt the ice crystal or even evaporate water droplets before replication is complete. These interrelated factors require careful design compromises. The task gets harder as the range of operating conditions is increased to cover higher air speeds and colder temperatures, and the task is further complicated by mechanical problems such as film sticking and elongation of sprocket holes.

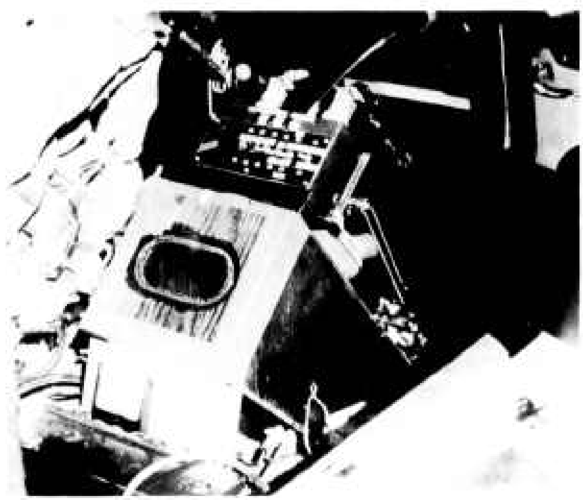
The roll-on coating wheel, as in Fig. D-1, proved to be reliable operationally. In the coating wheel method the moving film is pressed against the top edge of a thin, large diameter wheel causing it to rotate. The bottom portion of a wheel lies in a reservoir of the coating solution, and as the



Sampler on Nose of Apache. Solvent and coater wheel visible through glass.



Nose Cover Removed



Projector-viewer apparatus in right front cockpit.

Projector drive system, with enclosed supply reel and take-up reel.

Fig. D-1. 1963 CONTINUOUS SAMPLER IN APACHE AIRCRAFT

wheel rotates a stripe of this solution is transferred to the film at the point of contact. In practice the edge of this wheel, which is about 3 mm wide, is machined to form a trench on the order of 300 μ deep. In order to minimize the deposition of excess Formvar at the edges of the stripe, an adjustable scraper was fitted. This scraper consists of thin, stainless steel blades which are in contact with the perimeter and sides of the wheel and serve to wipe off any excess solution which adheres to these surfaces.

The vapor pressure of the solvents used is very high and any flow of air over the solution surface causes rapid evaporation. To prevent a flow of unsaturated air over the solution, the tank and film magazine portions of the system should be pressurized or sealed so that their atmospheres are in equilibrium with the stagnation pressure. This configuration also minimizes hardening of the Formvar solution and evaporative cooling prior to exposure at the window slot.

Both chloroform ($CH\ Cl_3$) and ethylene dichloride ($C_2H_4Cl_2$), as well as mixtures of both, have been used as solvents for the Formvar. The chloroform is the more volatile solvent, by a factor of 2-1/2 or 3. The melting point of chloroform is -63.5C, while it is only -35.5C for ethylene dichloride, and thus the use of chloroform is indicated at cold temperatures. The rapid cooling by solvent evaporation during Formvar hardening can be severe with chloroform, and so sometimes the use of ethylene dichloride is preferable.

Ice crystals seem to replicate best with a thin film (minimizing evaporative cooling and making the regulation of heat less critical) and dilute Formvar concentration (which gives the best replica resolution). Such a thin film tends to magnify troubles of skinning over the film before reaching the impaction area, which can have a bad effect on droplet replication and, to a lesser extent, on crystal replication. The conditions which are best for ice crystal replicas tend to permit flocculation of water droplets. Thick concentrations minimize flocculation. Thick film provides less droplet distortion but tends to blow off more in the air stream, especially when of dilute concentration.

It appears from flight tests that, with adequate drying heat, a concentration of between 2.5 per cent and 4 per cent of either solvent in the coater tank is about optimum. When the concentration is less than 2.5 per cent the air stream displaces the coating at relatively low air speeds, except for very thin films. When the concentration is greater than 4 per cent the replication efficiency appears to decrease.

There seems to be a reasonably broad range of film thickness and concentrations for good droplet collection and replication, or alternatively

for good ice crystal collection and replication, with either chloroform or ethylene dichloride. The ranges are extended with careful control of drying heat. There is a much more limited range of film thickness and concentration for good simultaneous collection and replication of coexisting droplets and crystals. Both droplets and crystals have been obtained at once with thin 1 per cent ethylene dichloride, and on other occasions with thicker film of 2-1/2 per cent chloroform (65 per cent) and ethylene dichloride (35 per cent) mixture.

All the potential difficulties mentioned were encountered during the 1963 field season, but nevertheless much of the data is still of considerable value.

Neither the drive motor nor the rest of the electrical system may be considered spark-proof, and therefore, in order to eliminate the possibility of what could be quite a violent explosion, it is recommended that a non-inflammable solvent such as chloroform be used rather than the ethylene dichloride. Since the chlorinated hydrocarbons and in particular chloroform are toxic and their effect is to some extent cumulative, the equipment should be mounted and vented in such a way that personnel are not exposed to sensible concentrations of vapor. The chloroform vapor in the cockpit area in the Apache in 1963 was extremely annoying to the crew.

Droplet Distortion

When an ice crystal impacts on the softened Formvar film, the subsequent replica is a perfect, hollow, three-dimensional casting of the crystal in the Formvar. If the impacting particle is a liquid droplet, the situation is much more complex because the droplet will distort. The Formvar will still encapsulate the droplet (probably in a millisecond for small droplets), the solvent will evaporate and leave a Formvar replica, and the droplet will eventually disappear by evaporating through the thin Formvar skin. However, the exact shape the droplet assumes will depend on the original spherical droplet diameter, the thickness of the Formvar coating, and the surface tensions of the Formvar solution to air and to water. As the solvent evaporates, the Formvar coating thickness changes, and the surface tensions change as the Formvar solution gets denser (and the solution concentration will get denser more quickly in the thin skin over the droplet than in the main film). These varying factors will keep readjusting the droplet shape until the Formvar solution viscosity increases to the point where no further shape change will take place (the Formvar gets so viscous it is effectively solid). For the practical utilization of the continuous sampler it is essential to establish the calibration factor, replica radius divided by original droplet radius, for various conditions of film thickness, film material, and droplet size.

Theoretical and experimental calibrations were made for the NRL-ONR project. The rough absolute calibration technique, conducted by R. Williamson of MRI, was an adaptation of the method employed by Farlow and French (1956). Small particles were put in a water sample, the sample was shaken (acoustically) to distribute the particles as uniformly as possible, and then the sample was used in an atomizer to create droplets. Assuming a uniform concentration of particles per unit volume of water, each droplet would contain a number of particles proportional to its volume. Thus the diameter of a droplet impacting on the Formvar could be ascertained by counting the small particles visible in the replica. Because of the statistical variations of the particle concentrations, many trials had to be made to give significant points on a replica diameter/droplet diameter curve.

The particles were the spores of the common mold, aspergillus niger. These were selected because they have the features of small size (about 3 μ diameter), fairly uniform size, do not dissolve in the solvents used, and have relative densities not far from 1. Tests were made with Formvar coating from 6 per cent and 3.5 per cent chloroform solutions. It turned out (as could have been anticipated) that the distortion was a function of the ratio of the droplet size or replica size to the final dry Formvar thickness (23 μ for the 6 per cent case and 10 μ for the 3 per cent case). Figure D-2 summarizes the results of the calibration.

Size Ranges

The small end of the size range of particles which can be treated by this sampler depends essentially just on collection efficiency. In all the present versions of the continuous sampler the film is curved around a longitudinal axis and fits snugly behind the slot. Thus to a first approximation the collecting surface represents a section of a circular cylinder, and so its collection efficiency can be computed from the curves presented by Langmuir and Blodgett (1945).

To illustrate typical values, Fig. D-3 shows the collection efficiencies computed for conditions which were representative of those on the Flagstaff cumulus studies. The curve for the stagnation point of the 1.2 cm diameter cylinder is one actually used in data reduction; the other two curves demonstrate the differences caused by using a larger cylinder or considering the whole cylinder rather than the stagnation point. Normally the particles are counted near the center of the film, near the stagnation point. When low concentrations of ice crystals are being detected, sometimes a much greater width of the film is used to increase the sampling volume. Ice crystals do not have spherical shapes and so for them a simple collection efficiency curve such as on Fig. D-3 is not appropriate. However, by far the majority of ice crystals in natural clouds have sizes for which the collection efficiency is greater than 0.8, and so the exact curve used for them is not important.

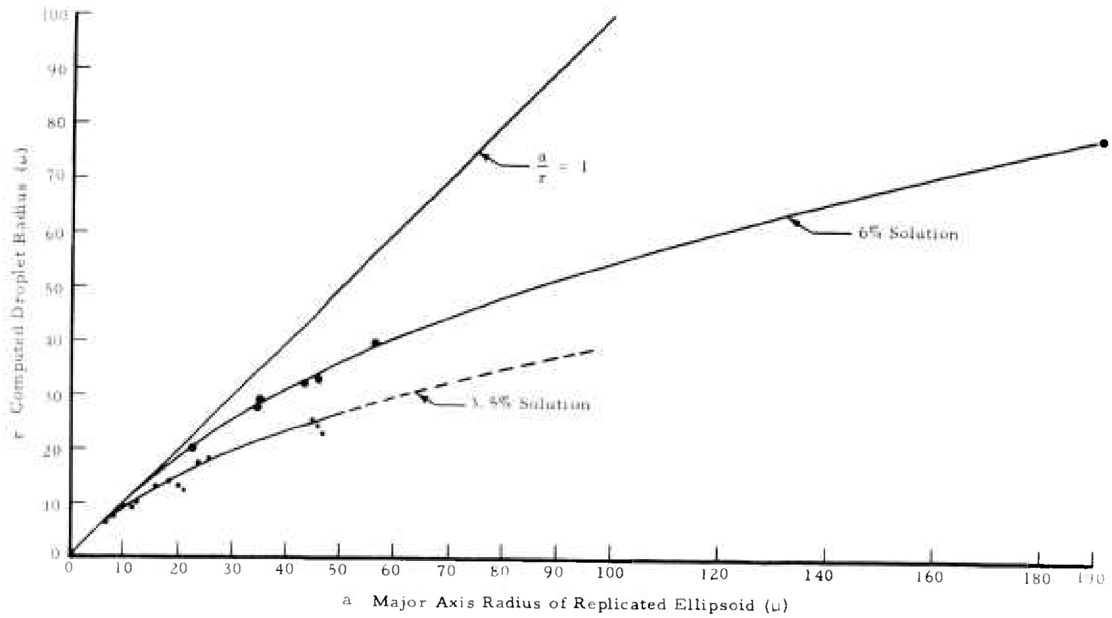


Fig. D-2a. Distortion Calibration with Aspergillus Niger Spores.

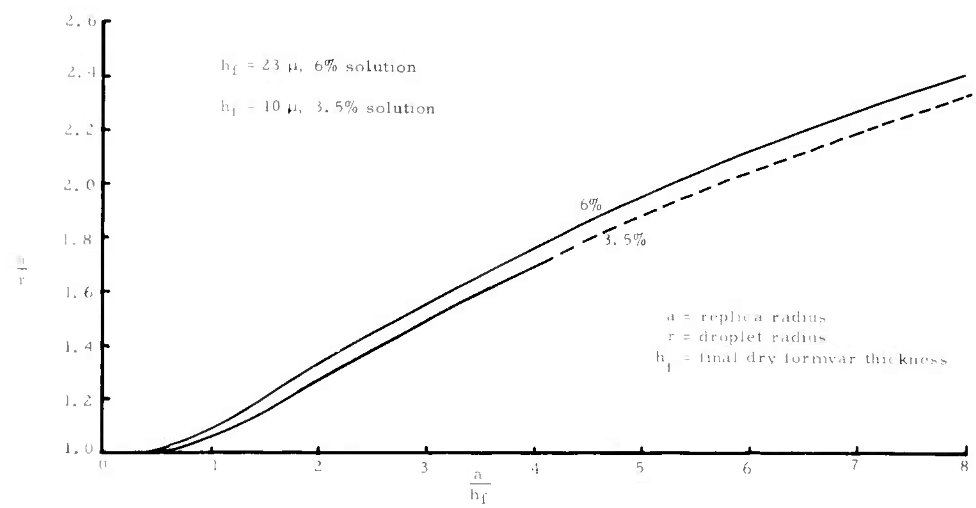


Fig. D-2b. Calibration Factor Related to Dry Formvar Thickness.

Fig. D-2. DISTORTION CALIBRATION.

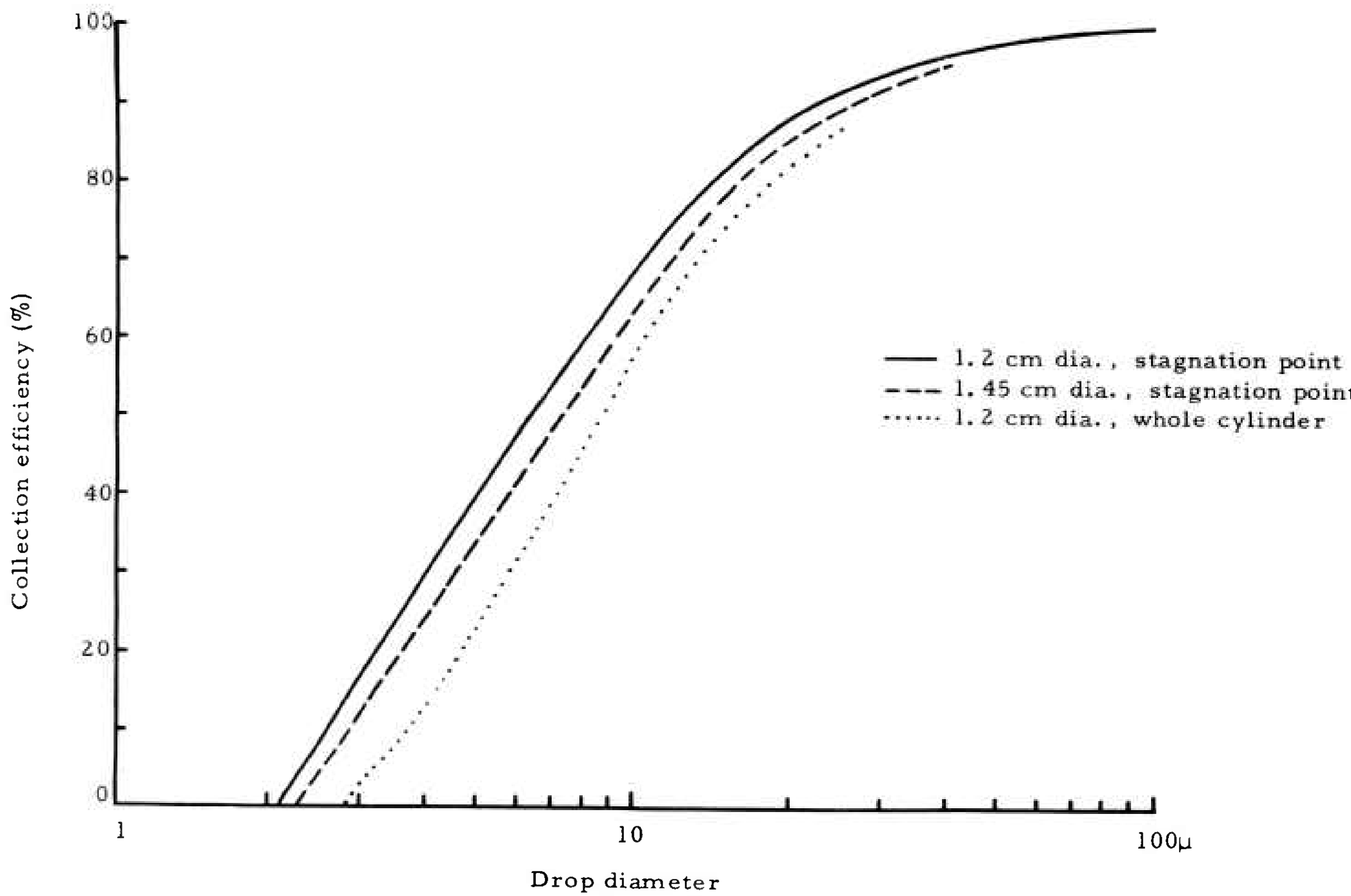


Fig. D-3. COLLECTION EFFICIENCY FOR DROPLETS IMPACTING ON A CYLINDER.

Curves representative of conditions at Flagstaff in summer cumulus clouds: true air speed 50 m per sec, temperature 0 C, pressure 500 mb.

The large end of the size range depends primarily on breakup during collection. Ice crystals of 100 μ may be cracked and 200 μ crystals broken; ice needles as long as 600 μ have been collected unbroken. When a graupel pellet hits the film, the replica has the appearance of a snowball which has struck a windshield; the number of graupel pellets can be counted, but the size of each is difficult to interpret.

Circular droplet replicas of even 150 μ diameter have been found on the film. The size of the corresponding droplets is not known, because the size correction factor for such extremes has not been found, but possibly the impinging droplet was on the order of 50 μ diameter. The maximum size having complete encapsulation must vary with concentration, but in any case the correction factor for the largest droplets will probably be somewhat indeterminate. As will be shown in Chapter I, Liquid Droplet Growth, larger droplets apparently make a large cleared spot on the film, and leave a single droplet of 70 μ diameter or larger. The size of the cleared spot is assumed comparable to the drop diameter. Rupe (1950) found that the formula:

$$\text{diameter (microns)} = \frac{1725}{\text{impact speed (m/s)}}$$

gives the largest size of a droplet which would not break on penetrating a kerosene surface. At 50 m/sec this corresponds to a diameter of 34.5 μ. Weickmann and aufm Kampe (1953) found the constant in the above formula to be increased by an order of magnitude for collection in castor oil.

Data Reduction

It has turned out to be most convenient to analyze the film by projecting it on a screen with a modified version of a standard stop-motion projector. For counting large particles such as big snow crystals and graupel the standard 16 mm projection lens system is used. For counting and examining small particles the lens system is replaced by a tube with the optics system from a microscope, usually set at 500 or 1000 power.

The main problem is to cope with the large amount of data generated each flight. At the present stage of development of the system, automatic data reduction of these replica records does not yet seem justified because manual methods can give concentrations and spectra quickly and without intricate apparatus. Human interpretation is necessary during data reduction of complex snowflake replicas and of poor quality droplet replicas.

The film records are first examined crudely by running them through at 16 frames per second. The eye and mind react quickly enough to ascertain the general distribution of drop sizes, the presence of ice crystals and graupel, and the general quality of record.

The next step for general cloud studies is to get the concentrations of droplets and crystals and the general size ranges. These counts can be made rapidly from representative frames. The droplet counts must be corrected for droplet distortion, and then the collection efficiency factor used to determine true concentration. These corrections are especially quick to apply when the droplet spectra are narrow. To facilitate correlating these data to the other cloud parameters recorded on an analog chart during the airplane traverse, it has proved convenient to plot the data on a chart driven from a gear on the projector. Figure D-4 shows the latest setup which has been employed on the USAERDL program and which has proved very satisfactory. The gear ratio is adjusted to put the particle information on the time scale of the cloud parameter records. Concentrations of water droplets, ice crystals, and graupel particles are graphed in different colors. As the film is run back and forth, feature after feature may be added to the chart, or one may analyze detailed features on the film while keeping reference to the gross features from the chart. When the sampler is run in the aircraft, usually at 10 frames/sec, three event markers on the cloud parameter chart record every 1, 10, and 100 rotations of an idler wheel on the film, corresponding to every 10, 100, and 1000 frames. Thus the sampler data (or the data on the linked chart) can easily be exactly correlated to the cloud data.

For detailed case studies complete size spectra and accurate concentrations are required. A data compilation technique which has proved simple and effective is to move a strip of paper around the projected frame, putting the strip's left edge on the left edge of each replica image and making a mark on the strip at the right edge of the replica image. Then the dots are counted in the size categories, to provide spectra after the droplet distortion and collection efficiency corrections are applied. Rather than recording complete spectra it is often satisfactory to record only the concentration and the mean and standard deviation of the distribution. Obtaining the standard deviation is facilitated by putting a micron scale vertically on the strip (perpendicular to the droplet size scale which goes horizontally from left to right). Then slide a probability scale down the strip, with the 50 per cent cumulative probability line matching the horizontal position of the median droplet. Mark the strip at drop sizes corresponding to various cumulative probabilities, and make a best fit line through these points. Read off the micron size of one standard deviation (50 per cent to 84 per cent or 50 per cent to 16 per cent cumulative probability).

Conclusions

The main details of the sampler are given in the paper by MacCready and Todd in Part A of the MRI Final Report to USAERDL. Additional

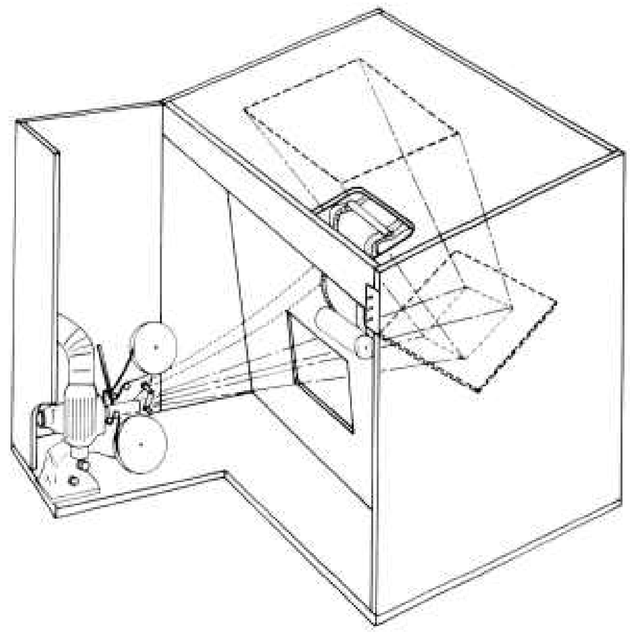


Fig. D-4a. General View of the Projector Analyzer.

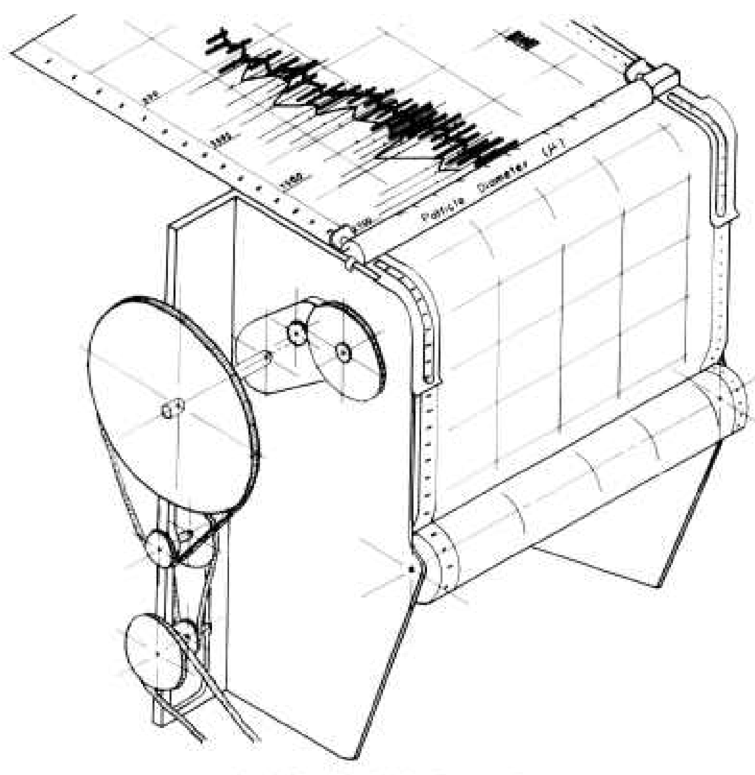


Fig. D-4b. Detail of the Chart and Chart Drive.

Fig. D-4. THE LINKED CHART-PROJECTOR ANALYZER FOR THE CONTINUOUS SAMPLER.

information on the utilization of the device is contained in subsequent chapters of this report. There are two significant recent achievements in the use of this device, as shown in Chapters H, I, and K:

1) The correction factors for droplet-to-replica size and for collection efficiency appear to be valid, inasmuch as the total liquid water contents computed from the size spectra agree approximately with the theoretical expected liquid water content in unmixed cores. This gives confidence to the calculations of droplet concentration and coalescence.

2) The presence of large droplets or drops can be found from the sampler record.

E. Flow Patterns and Convective Precipitation in the Wake of an Isolated Peak.

Summary

Observations have been made in the Flagstaff, Arizona, area of the influence of the isolated San Francisco Peaks on summer convective cloud activity. Most of these cloud effects can be associated with wave flow patterns induced by the Peaks and appear to be analogous to wave effects co· ;idered to be typical of flow over ridges.

In addition to the wave effects, a major storm area often develops in the lee of the Peaks at downwind distances up to 25-30 miles. This storm area is frequently the first precipitation development in the region and, in some cases, may produce the only major precipitation for the day. Wind, moisture and temperature environments control the existence and location of the wake storm. It is suggested that the primary factor producing the storm is the converging airflow in the surface layers behind the Peaks. The wake storm represents an unusual opportunity for modification studies of major storms by providing a repetitious storm development, a portion of which can serve as an unseeded control for the modification experiment.

Introduction

Observational evidence of the effects of isolated mountains on cloud forms is largely confined to cases of stable airflow patterns and is generally shown (e.g. WMO Tech Note 34, 1960) as cap clouds, lenticulars and banner clouds. Glass and Carlson (1963), however, have investigated the convective effects of the isolated San Francisco Peaks near Flagstaff, Arizona. Their analysis shows that the early convective activity on the day of study occurred slightly downwind of the Peaks and may have resulted from heated slopes on the windward side of the mountain mass.

For several years Meteorology Research, Inc. (and its associate Atmospheric Research Group) has conducted summer cloud physics studies in the Flagstaff area. During the early phases of these studies primary attention was given to individual clouds and in-cloud investigations. During the past two years, however, interest has grown in the mechanism of organization of the larger Cb storms in the area and it has been possible to observe a variety of mountain effects on the cloud activity in the region. This variety results from differences in wind, stability and moisture content and an outline of these variations is given in the following study.

Of primary interest has been the occasional development of a well-organized storm system in the wake of the mountain mass under appropriate conditions of wind, moisture and stability. This storm does not result from heating of the mountain slope itself but forms downwind of the Peaks in the convergent flow behind the mountain. The organized nature of the flow is evidenced by the long duration of some of the wake storms and the localized nature of the storms immediately behind the Peaks.

The wake storms represent an example of organized convective activity in contrast to the random cumulo-nimbus storm development that frequently occurs as a result of direct heating of the slopes. The non-random nature of the wake storm development suggests that its organizational mechanism may be easily investigated over a period of time and that, once studied in detail, the wake storm offers a unique opportunity for controlled investigations of modifications of large scale storm systems.

The present study is divided into two portions: a) a summary of the effects of the mountain on the observed cloud forms and the flow patterns associated with these effects and b) more detailed observations of the wake storm development and its requisite environmental conditions.

Terrain and Meteorological Environment

The San Francisco Peaks are of volcanic origin and represent a comparatively isolated mountain mass relative to the surrounding terrain. Figure E-1 shows a topographic map of the region near Flagstaff. The San Francisco Peaks (Humphreys and Agassiz Peaks) rise to near 12,000 ft from a general level of about 7000 ft in the surrounding area. Although a few small mountains exist to the northwest and east of the Peaks, Humphreys and Agassiz Peaks clearly dominate the terrain in Flagstaff area and closely approximate an isolated mountain mass.

Typical wind flow directions during July and August are from the southwest or southeast with infrequent, temporary directions to northerly components. Southeasterly winds bring moist air from the Gulf of Mexico into the Flagstaff area and result in extensive shower activity. Southwesterly winds tend to be much drier and more stable although isolated showers frequently develop. Temperature lapse rates aloft are determined primarily by large scale subsidence and tend to be stable for dry vertical motions but are frequently convectively unstable, particularly for the moist, southeast wind conditions.

Under light wind conditions, the isolated mountain mass serves as a highly effective heat source for the preferential development of cumulus activity. Major thunderstorm developments frequently occur as a result of this activity. This study is not concerned with these developments but rather with the storm areas which develop downwind of the Peaks and whose roots are not found on the heated mountain slopes.

Data Sources

The data used in this investigation were obtained from five sources: 1) Radar film records of the MR-4 (3 cm) and M-33 (10 cm) PPI scopes, 2) Radiosonde runs taken at Flagstaff Airport in 1961 and at Navajo Ordinance Depot and Winslow in 1962 and 1963, 3) Time-lapse cloud film taken at Gray Mountain, Valle Camp, Rimmy Jim and Flagstaff Airport, 4) Slow-lift balloon tracks obtained from the track component and plotter of the M-33 radar system and 5) Single theodolite balloon runs taken behind the peaks. These locations are shown in Fig. E-1.

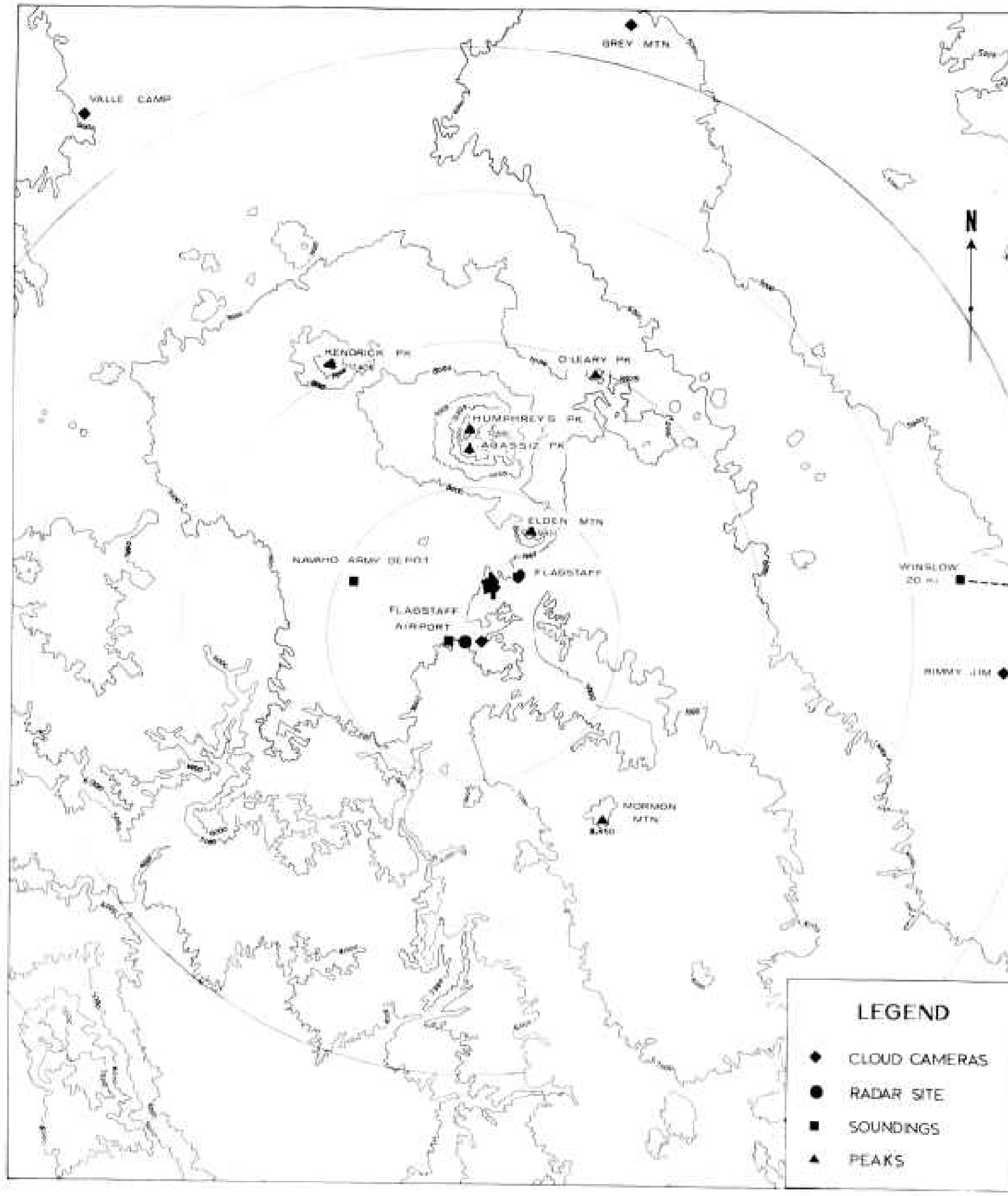


Fig. E-1. THE SAN FRANCISCO PEAKS IN NORTHERN ARIZONA. The range circles are every 10 miles.

Airflow Patterns

Forchtgott (1949, 1951) has provided commonly used pictorial representations of the flow patterns over ridges and an isolated peak. These are shown in Figs. E-2 and E-3. Although Forchtgott was able to observe a variety of flow conditions over ridges, apparently only one of these, "standing eddy streaming" (Fig. E-3) was observed sufficiently often in association with an isolated peak to be drawn in pictorial form. Forchtgott himself (1951) states that other flow patterns must exist for isolated peaks and it is reasonable to expect that some of these patterns may resemble several of the better-documented ridge flows shown in Fig. E-2.

Principal theoretical work on flow over an isolated peak has been accomplished by Wurtele (1957), Palm (1958), Scorer (1956), Crapper (1959) and Sawyer (1962). One of the features these solutions have in common is that the wave train behind the peak is confined to a triangular area with apex at the mountain, somewhat similar to the bow wave of a ship.

These solutions (e.g. Wurtele, Fig. E-4) have predicted a crescent-shaped lee wave train of alternating updraft and downdraft velocities downwind of the peak. Lenticular clouds of this shape have been reported frequently (e.g. Abe 1932) and were reproduced by Abe (1941) in a wind tunnel study. Thus the lee wave systems pictorially represented as wave streaming and rotor streaming (Fig. E-2) might be expected to appear as crescent-shaped regions as a result of the three-dimensional character of the flow around the isolated peak. These patterns, however, should appear similar to those shown in Fig. E-2 in the vertical cross section along the centerline formed by the peak and the wind direction.

For lighter wind conditions, Forchtgott (Fig. E-2) shows a vertical displacement of the streamlines over the ridge but without proper environment conditions to initiate a lee wave system. Downwind of the ridge the flow quickly returns to its normal pattern. Evidence of this type of motion is primarily seen in cap clouds (WMO, TN34, 1960). In the Flagstaff area convective activity over the peak tends to disturb the flow pattern to the extent that "laminar streaming" should be rare, particularly during the daytime. The "standing eddy streaming" case shown in Fig. E-2 has been redrawn by Forchtgott to include the effects of flow around the mountain and is shown in Fig. E-3 as typical flow around an isolated peak. As represented in the figures the "standing eddy streaming" case does not include the development of a lee wave train and hence cannot be the same type of flow as shown by Wurtele's solution and as evidenced by the crescent-shaped lenticular clouds.

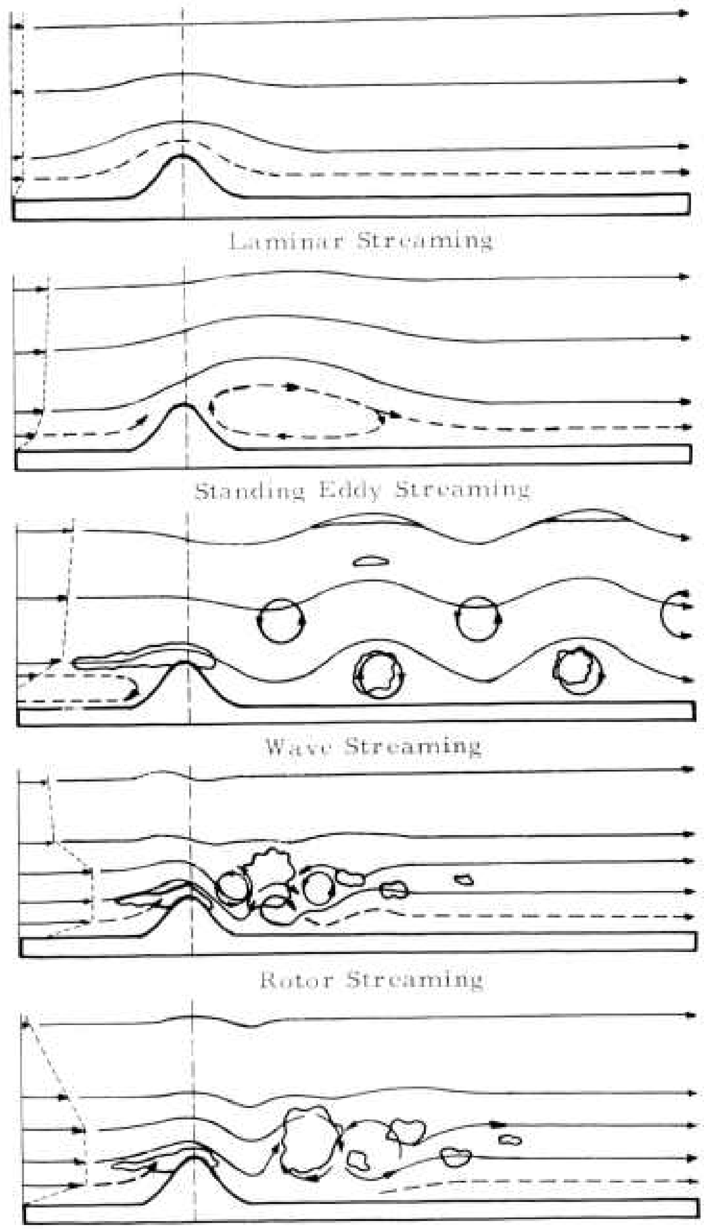


Fig. E-2. FORCHTGOTT'S (1949) CLASSIFICATION OF TYPES OF AIR FLOW OVER RIDGES.

Wind profile indicated to the left in each case. After Alaka (1960).

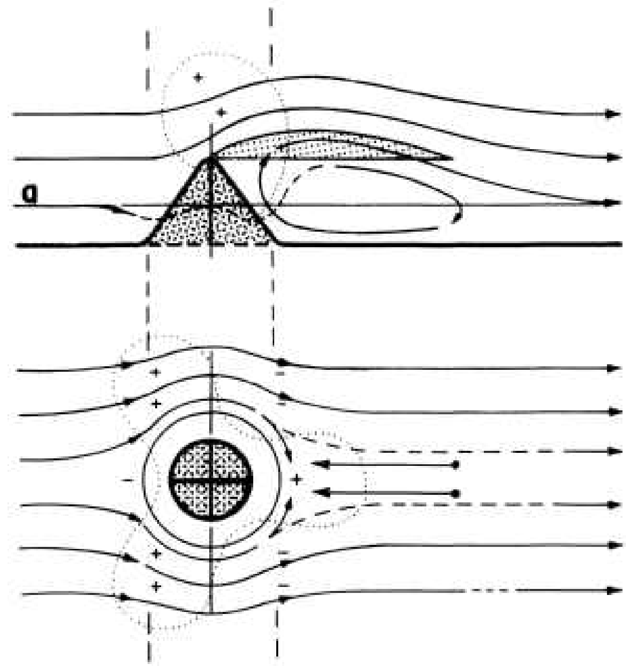


Fig. E-3. SIDE AND GROUND PLAN VIEWS OF STREAMLINES IN THE VICINITY OF A CONICAL HILL.

The lower diagram shows the flow in the level "a". Positive and negative vertical velocity components are denoted by + and - respectively. After Forchtgott (1951).

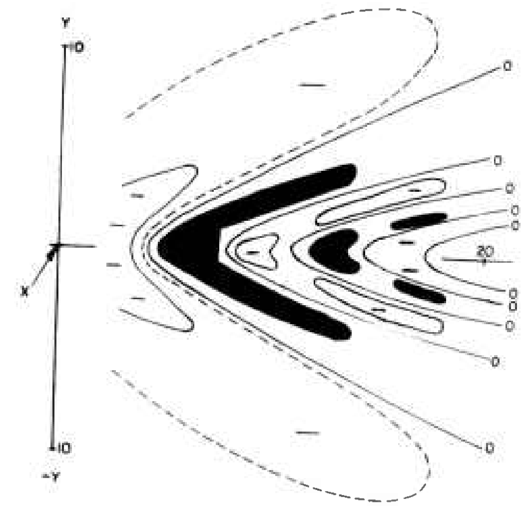


Fig. E-4. VERTICAL VELOCITY FIELD DOWNWIND OF A ROTATIONALLY SYMMETRICAL OBSTACLE, ILLUSTRATING CRESCENT-SHAPED UPDRAFT AREA.

Strong updraft areas are darkened. Principal downdraft areas are shown by minus signs. X denotes center of obstacle. Wind flow comes from left. After Wurtele (1953).

Observed Cloud Forms at Flagstaff

a) 15 July 1963 - On the morning of 15 July, a crescent-shaped lenticular cloud was observed downwind of Humphreys Peak. Figure E-5 shows the development of the cloud. Calculations of the cloud position indicate that the front edge of the cloud was approximately 3-1/2 - 4 miles downwind of the peak and the cloud base was about 19,000 feet MSL. Figure E-6 shows the vertical wind profile as observed at Navajo Ordinance Depot on 15 July. This profile is similar to the schematic wind profile shown by Forchtgott in Fig. E-2 for the wave streaming category. Conformity with the form of the theoretical solutions (Wurtele and others) suggests the formation of a lee wave train downwind of the Peaks.

The lenticular cloud on 15 July existed in the same location from 0800 to 1445 LST and then reappeared at about 1730 LST. During the afternoon, decreases in the low level stability apparently reduced the effect of the mountain on the flow pattern, presumably as a reduction in wave amplitude.

b) 26 July 1963 and 10 August 1962 - One of the frequent cloud forms observed in the Flagstaff area is a rather turbulent series of short-lived clouds approximately 5 miles downwind of the Peaks. Under proper wind and moisture conditions, first cumulus developments of the day occur in this area. Two examples of this cloud pattern are shown in Fig. E-7. On 26 July 1963 a series of small cumulus developed in the location shown in the figure. These clouds were the only developments visible during the period 0800 to 1000 LST. The clouds exhibited a short lifetime of 5-10 minutes but were quickly replaced by similar clouds in the same location. By 1100 LST this development had disappeared as other cumulus activity began in the surrounding areas.

On 10 August 1962 a similar pattern occurred and an example of the downwind cloud development is shown in Fig. E-7. The shredded character of the cloud is typical of highly turbulent flow patterns rather than the normal convective activity. Potential temperature surfaces immediately downwind of the Peaks were mapped out by aircraft traverses and are shown in Fig. E-7. The cloud pictured in the figure occurred in the turbulent area about 5-6 miles downwind of the mountain and was highly transitory in nature, changing shape very rapidly. This cloud pattern was observed until about 1100 LST.

Surface wind patterns (directed toward the mountain at low levels) and air trajectories assumed from the potential temperature plots of Fig. E-7 indicate that the associated flow pattern is a rotor flow similar to that shown by Forchtgott in Fig. E-2 for ridges. Wind profiles for 26 July 1963 and 10 August 1962 are shown in Fig. E-6 and clearly indicate the stronger velocities required for this type of flow.

0900 LST

1000 LST

1100 LST

1200 LST

1300 LST

1400 LST

1500 LST

Fig. E-5. DEVELOPMENT OF THE CRESCENT-SHAPED CLOUD DOWNWIND OF THE PEAKS ON 15 JULY 1963.

Photographs were taken looking due north with the wind across the peaks from 240° at 20 knots. The time (LST) is shown below each photograph.

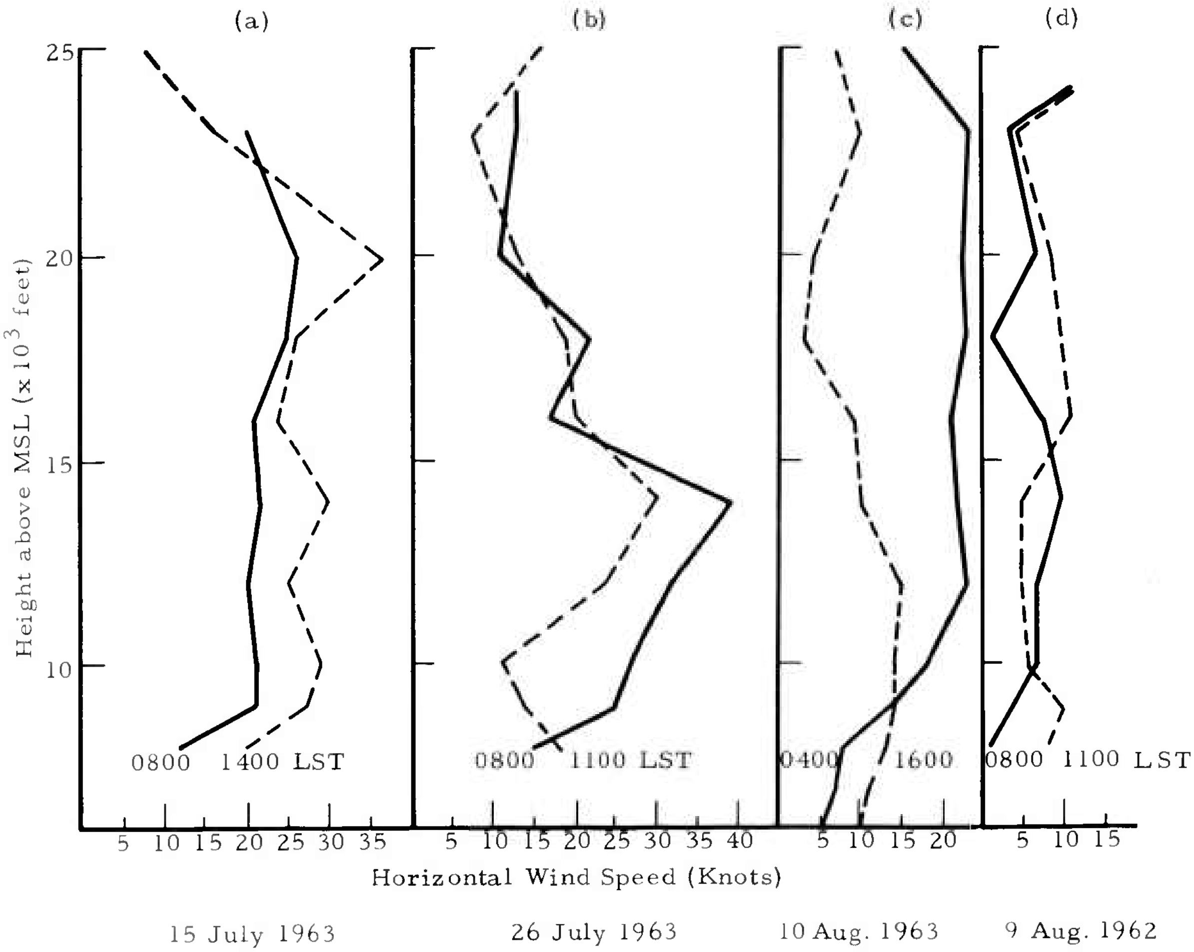
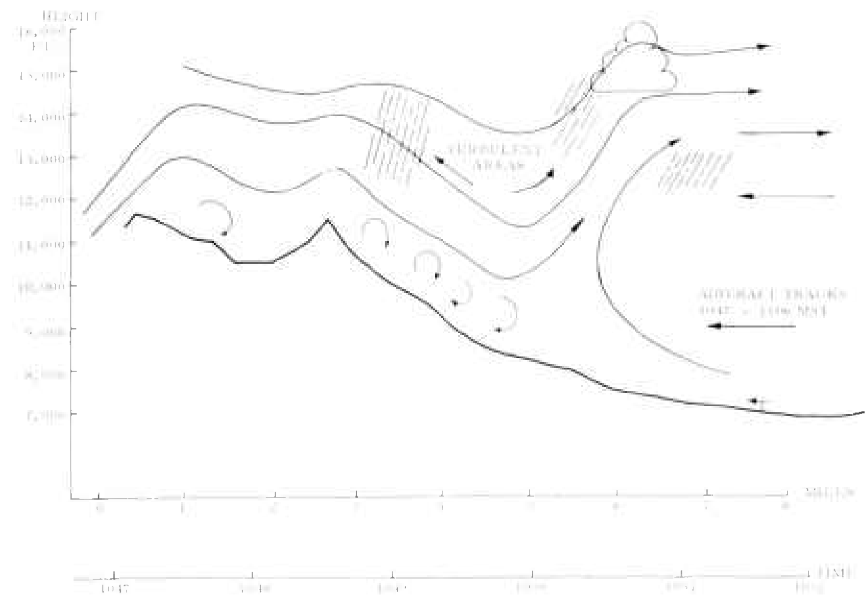


Fig. E-6. VERTICAL WIND PROFILES FOR THE DAY DISCUSSED IN THE TEXT.

Profiles (a)(b) and (d) were taken at Navajo Army Depot, Profile (c) at Winslow. Time (LST) of each is shown at its base.

7a. Rotor cloud observed on 26 July 1963. Photograph looking due north with wind across the peaks from 240° at 32 knots.

7b. Rotor cloud observed on 10 August 1963 in approximately same location as 7a.



7c. Vertical structure of the wake on 10 August 1963 at same time as photograph shown in 7b.

Fig. E-7. OBSERVATION OF ROTOR CLOUD AND ITS ASSOCIATED FLOW STRUCTURE.

In both cases, 26 July and 10 August, the downwind cloud development was the only cumulus activity of consequence for a considerable period. In each case increased instability during the late forenoon decreased the effect of the mountain on the flow and visual evidence of the rotor flow disappeared. Low moisture content on both days limited cumulus activity in other areas and permitted observation of the rotor flow for a considerable period of time.

c) 9 August 1963 - Occasionally, in the Flagstaff area, the first cumulus activity of the day resembles the "standing eddy streaming" category of Forchtgott (Fig. E-3). This is illustrated in Fig. E-8 by a cloud photograph taken at 1002 LST and a subsequent radar echo location at 1013. Winds on 9 August were light southeasterly (see Fig. E-6) and the cloud location and the radar echo are shown displaced 3-5 miles downwind of Humphreys Peak. Time-lapse films of the cloud development clearly show the main cloud base in a downwind direction from the peak where it could not have been formed in upslope air from the heated, windward slope of the Peak.

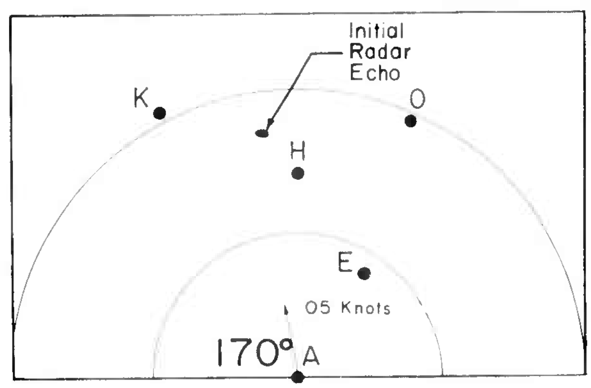
As shown by Forchtgott, under light wind conditions, air tends to flow around the peak and up the lee slope. As in the case of 9 August, this may be a more effective cumulus cloud source than the heated mountain slope. This type of flow pattern, generated by low velocity winds, tends to be disrupted easily by general convective heating of the mountain itself and, for this reason, does not occur as frequently in the summer studies at Flagstaff as it might in other meteorological regimes.

Wake Storm Development

a) Observational Evidence - It is frequently observed in the Flagstaff area that the earliest thunderstorm development of the day occurs some distance downwind of the Peaks rather than over the heated slopes. Favorable environmental conditions for this development occurred on 6, 7, 8 and 9 August 1963. Radar echoes are shown in Figs. E-9 - E-12 for the portions of the days when the wake storm was the only storm development in the Flagstaff region. Terrain echoes have been removed from the figures for clarity. Wind directions and velocities at 14,000 ft MSL (2000 ft above the peak) are also shown in the figures.

Figure E-9 shows a major storm area developing about 10 miles downwind of Humphreys Peak at about 0930 and continuing through 1130 LST. Around 1030 a parallel development occurred in the lee of the smaller O'Leary Peak. These storm areas are not continuous for the two-hour period at one location but form, drift downwind and are

a. Storm development at 1002 LST. Photograph was taken looking due north with the wind across the peaks from 170° at 5 knots.



b. Schematic representation of the PPI scope at 1013 LST. Range markers every 10 miles. Arrow indicates wind at 14,000 feet.

Fig. E-8. STORM OF 9 AUGUST 1963 ORIGINATING FROM RETURN FLOW UP THE LEE SLOPE.

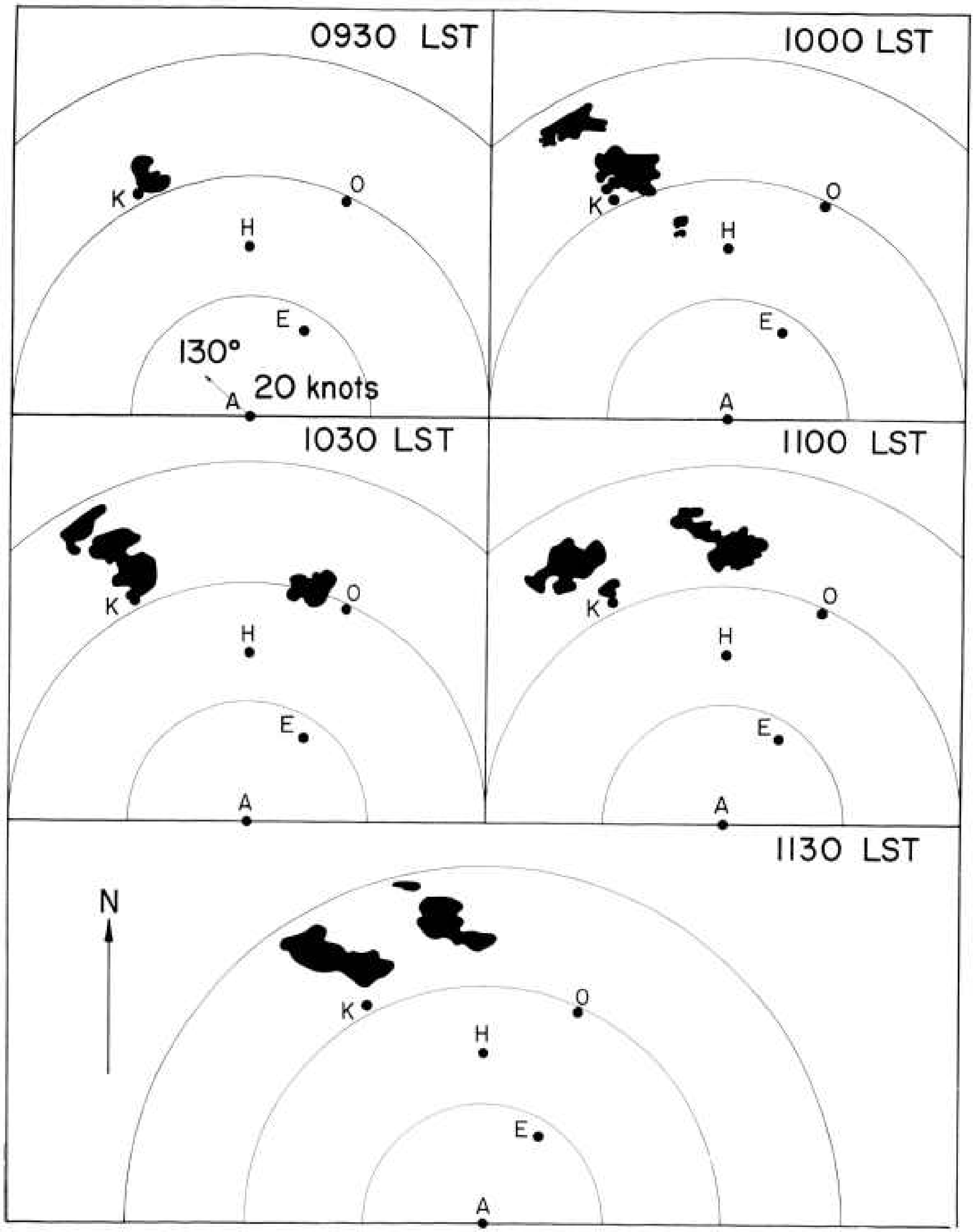


Fig. E-9. SCHEMATIC REPRESENTATIONS OF THE M-33 PPI SCOPE AS IT APPEARED ON 6 AUGUST 1963.

Range markers every 10 miles. Arrows indicate wind at 14, 000 ft. Small dots denote location of important landmarks: A - Flagstaff Airport, E - Elden Mtn., H - Humphreys Peak, O - O'Leary Peak, K - Kendrick Peak. Time (LST) is shown in the upper right of each representation.

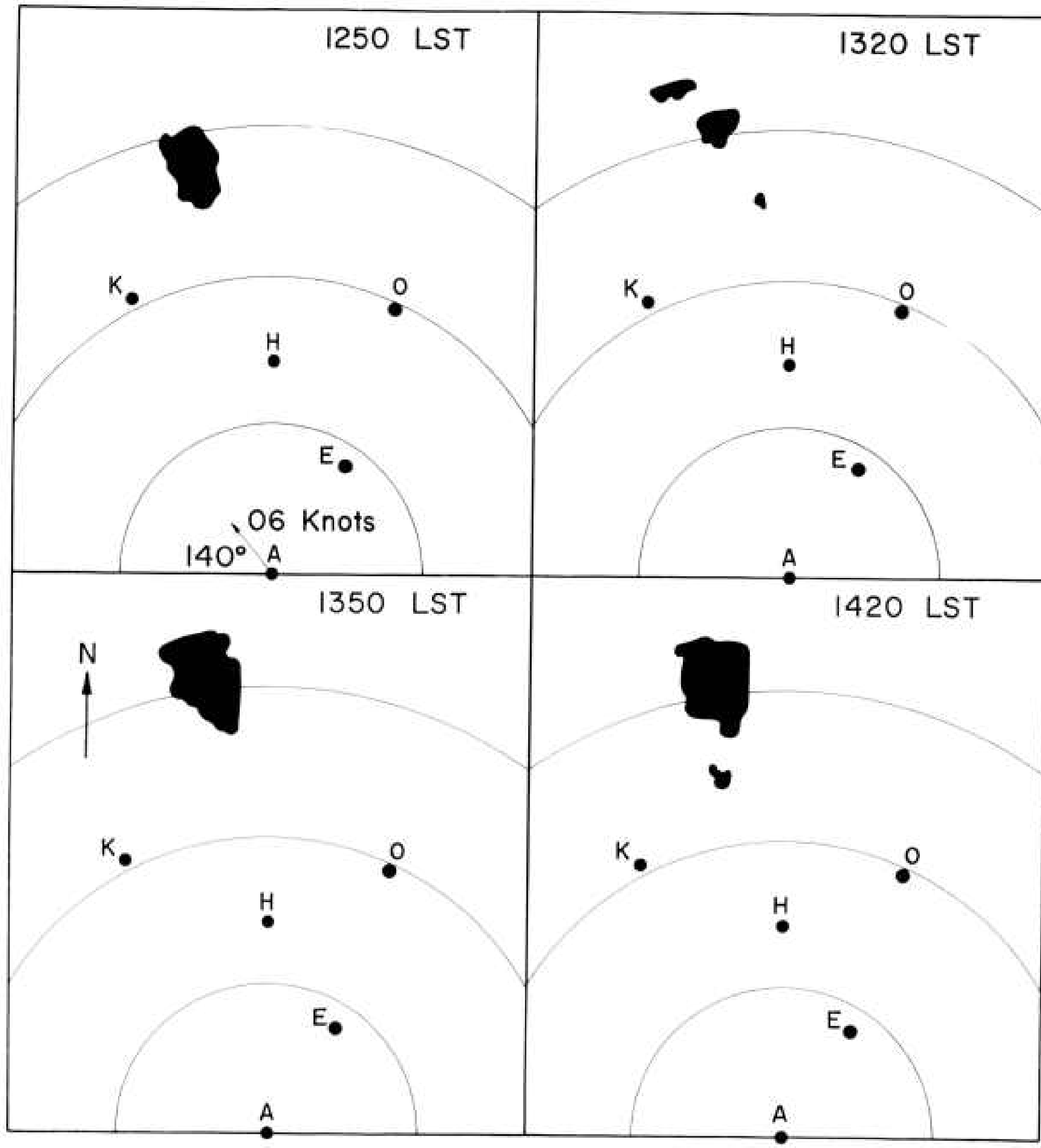


Fig. E-10. SCHEMATIC REPRESENTATIONS OF THE M-33 PPI SCOPE AS IT APPEARED ON 7 AUGUST 1963.

Symbols same as those used on Fig. E-9.

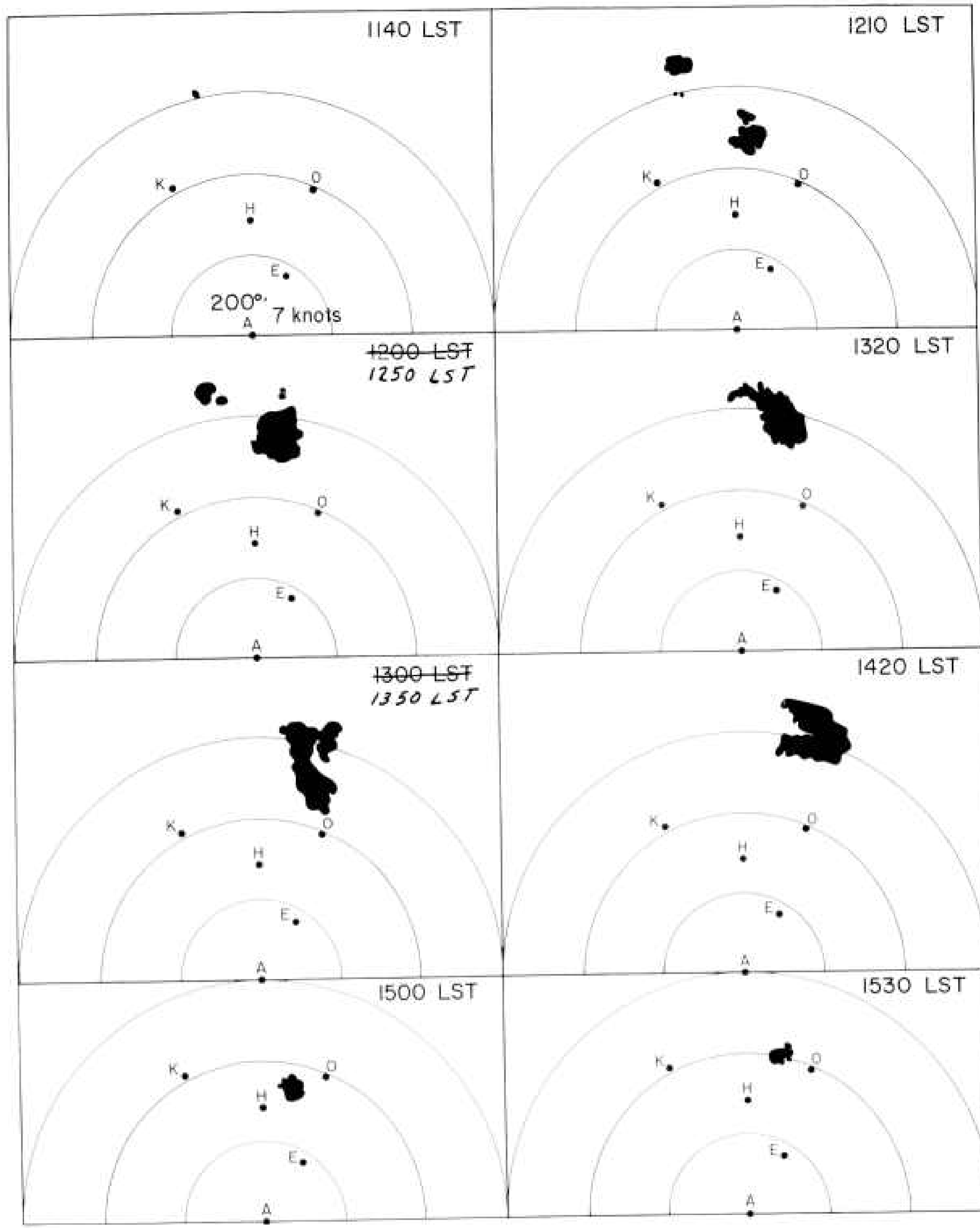


Fig. E-11. SCHEMATIC REPRESENTATIONS OF THE M-33 PPI SCOPE AS IT APPEARED ON 8 AUGUST 1963.

Symbols same as those used on Fig. E-9.

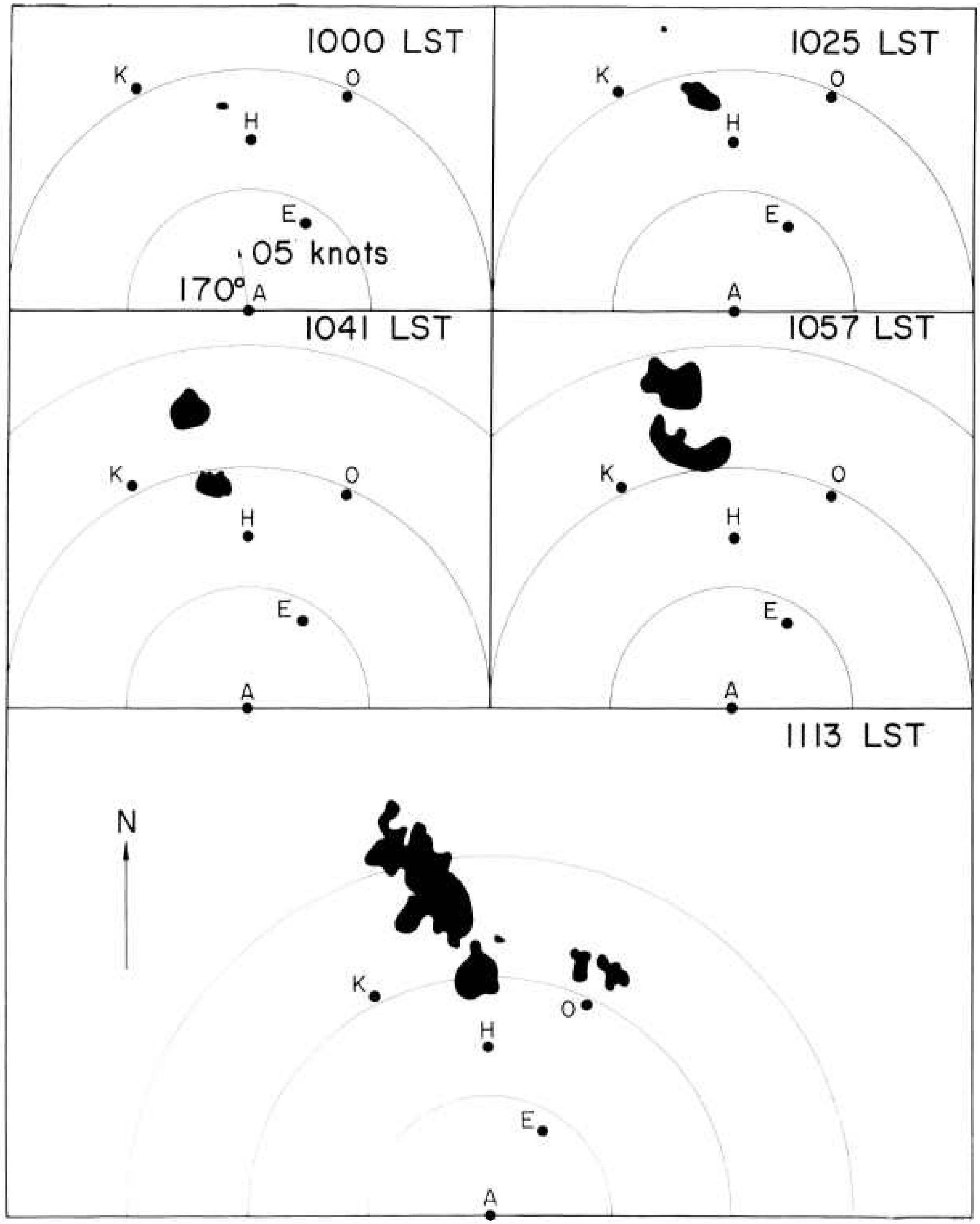


Fig. E-12. SCHEMATIC REPRESENTATIONS OF THE M-33 PPI SCOPE AS IT APPEARED ON 9 AUGUST 1963.

Symbols same as those used in Fig. E-9.

replaced by another storm which begins in the same region. The localized nature of the echo generating area is clear evidence of the organized nature of the flow which forms these storms.

Figure E-10 shows a storm area about 15-20 miles downwind of Humphreys Peak during the period 1250-1420 LST. In Fig. E-11 on 8 August, the downwind location of the storm area was 15-20 miles from the Peak. On 9 August (Fig. E-12) one small storm area developed immediately behind the peak (see previous section) and was immediately followed by the major storm development about 10 miles downwind. The principal environmental change from 8 August to 9 August was a decrease in wind velocity aloft.

b) Frequency of Occurrence - In order to obtain a frequency of occurrence of wake storms a subjective definition was established. Following the patterns shown in Figs. E-9 - E-12 a wake storm was defined to be a persistent, radar echo downwind of the Peaks which was the dominant echo in the region. On this basis, during the summers of 1961-1963 there were a total of 25 wake storm days and 27 non-wake days during the period of approximately 10 July - 15 August. On the remainder of the days, observations were not available for determining the appropriate category. On a large number of the 27 non-wake days, mountain cloud effects were observed (e.g. 15 July and 26 July 1963) but there was insufficient moisture to develop a wake storm.

For the 25 wake storm days the mean duration of each individual radar echo was about 44 minutes. This suggests a series of major storm areas in the wake since Battan (1953), for example, finds an average life listing of the simple convective radar echoes to be about 23 minutes.

c) Relation to Meteorological Environment - During the analysis of the radar echoes it was observed that the downwind distance of the storm from the Peaks tended to vary with wind speed. Figure E-13 shows this relation for all 25 wake storm developments during the 1961-63 period. An increasing distance with increasing 14,000 ft wind speed is shown in the figure in spite of considerable scatter in the data.

Since moisture is required for the convective storm development, the occurrence and non-occurrence of wake storms is shown in Fig. E-14 as a function of 0800 dew point at the Flagstaff Airport as well as 14,000 ft MSL wind speed. Most of the wake storms occur in an oval area, outlined on the graph. Although the exact boundaries of this area cannot be defined with the present data, it may be inferred from the general region that low moisture tends to inhibit the storm development (only cumulus clouds appear) and high moisture values generally signify that

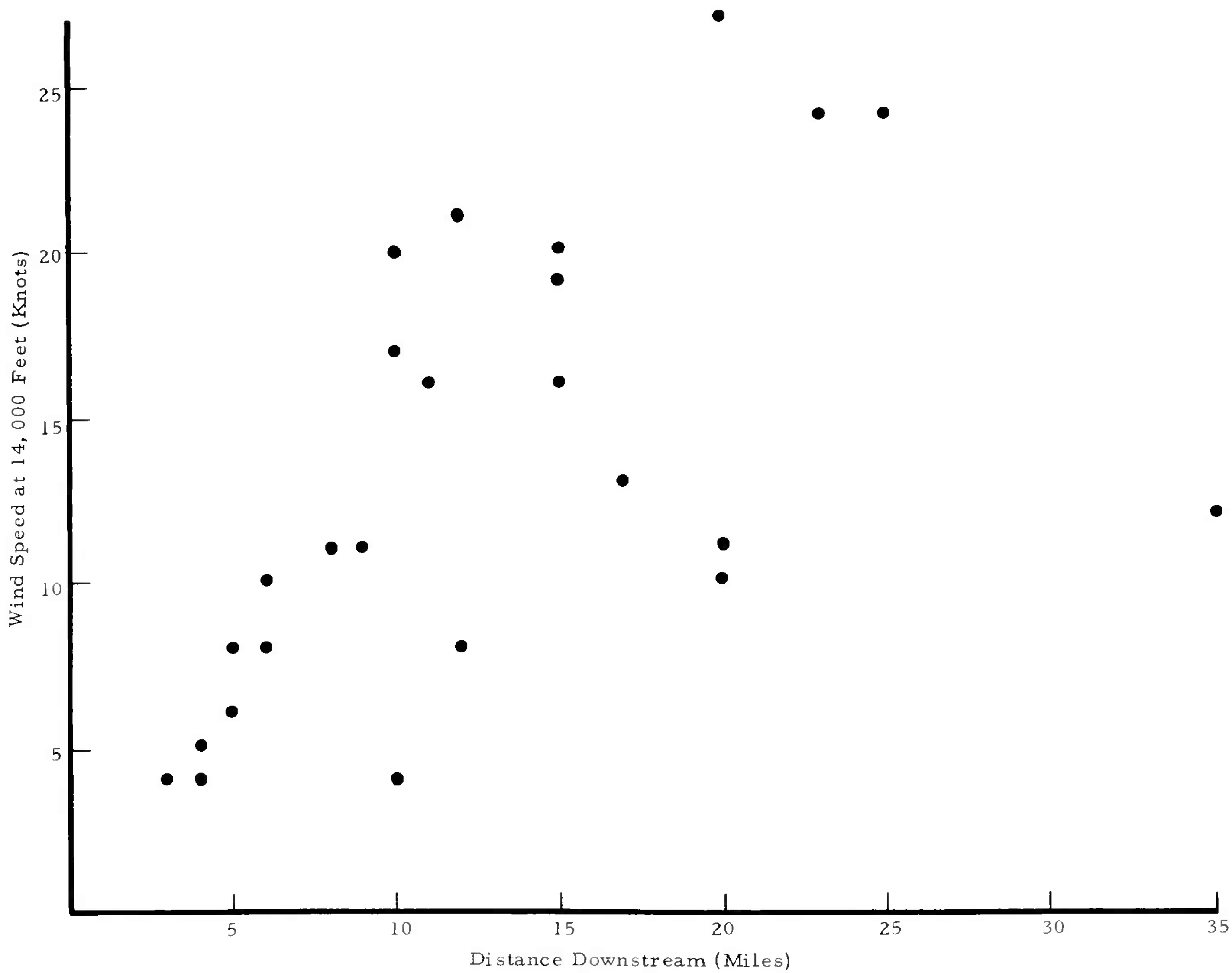


Fig. E-13. PLOT OF DOWNWIND DISTANCE OF THE WAKE ECHO VS. HORIZONTAL WIND SPEED AT 14,000 FEET.

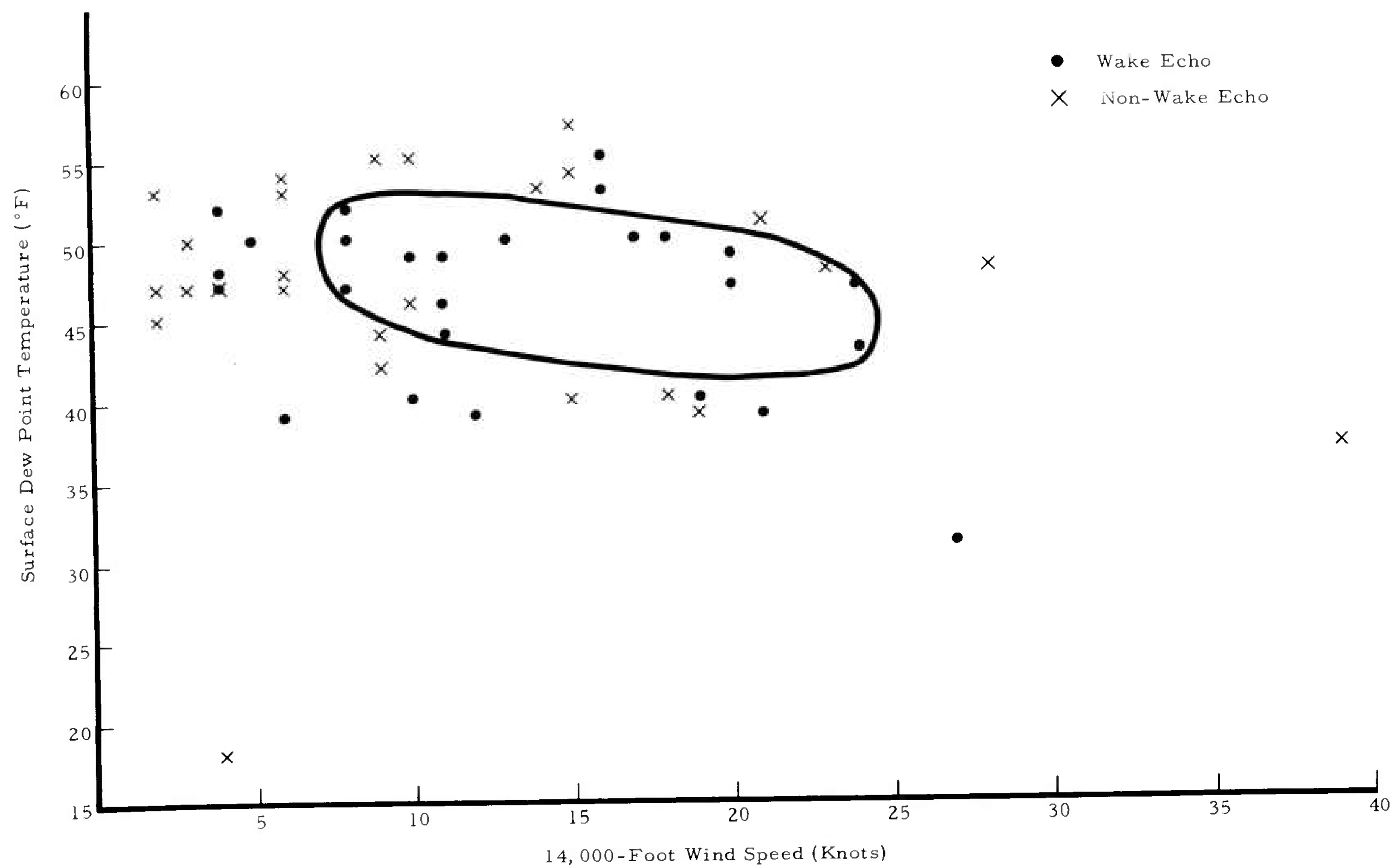


Fig. E-14. A PLOT OF SURFACE DEW POINT TEMPERATURE VS. HORIZONTAL WIND SPEED AT 14, 000 FEET, SHOWING THE CONDITIONS OF WAKE ECHO OCCURRENCE.

convective activity will appear throughout the area and lead to a disorganization of the wake flow. Low wind speeds tend to be associated with non-wake days since the wake is poorly organized and the slope heating dominates the storm development. There are few high wind cases outside the oval area but this condition may inhibit the wake storm due to excessive shear.

Single theodolite pibals were taken in the lee of the Peaks on 8 August and 9 August in an attempt to study the horizontal wind flow at various levels in the wake. Wind directions determined on 9 August at a number of locations are shown in Fig. E-15. Also shown for reference is the 14,000-foot MSL wind and the general location of the storm region. A general inflow area is seen to exist to the southeast of the storm area at levels to 4000-6000 ft above the terrain. Above this layer abrupt changes to the undisturbed flow direction occur and are shown in Fig. E-15. Surface wind measurements in this inflow region at regular intervals through the morning indicated that the easterly to southeasterly flow was continuous at least until 1300 LST when the observations were terminated.

Discussion

Observations have been given of the effects of wave patterns on cloud developments behind the isolated San Francisco Peaks. Many of these can be explained in terms of the typical patterns associated with flow over ridges. The wake storm development, however, has various characteristics which distinguish it from wave flow effects:

a) The wake storm occurs farther downwind than the previously observed wave effects. A second or third downwind wave would have to be employed to explain the wake storm as a wave development. For isolated peaks these downwind waves frequently decrease rapidly in amplitude with downwind distance.

b) The wake storm requires a considerable surface heating effect for its development since it does not normally occur before 1000 LST. The wave effects are diminished by this time due to increased instability in the air layers near the ground.

c) The wake storm may occur with wind flows as low as 5-10 knots at the level of the top of the peak. Wave effects over an isolated peak should be relatively small for these wind velocities.

Convergent flow occurs in the lee of the mountain through a considerable layer as shown in Fig. E-15. Somewhat similar surface flow

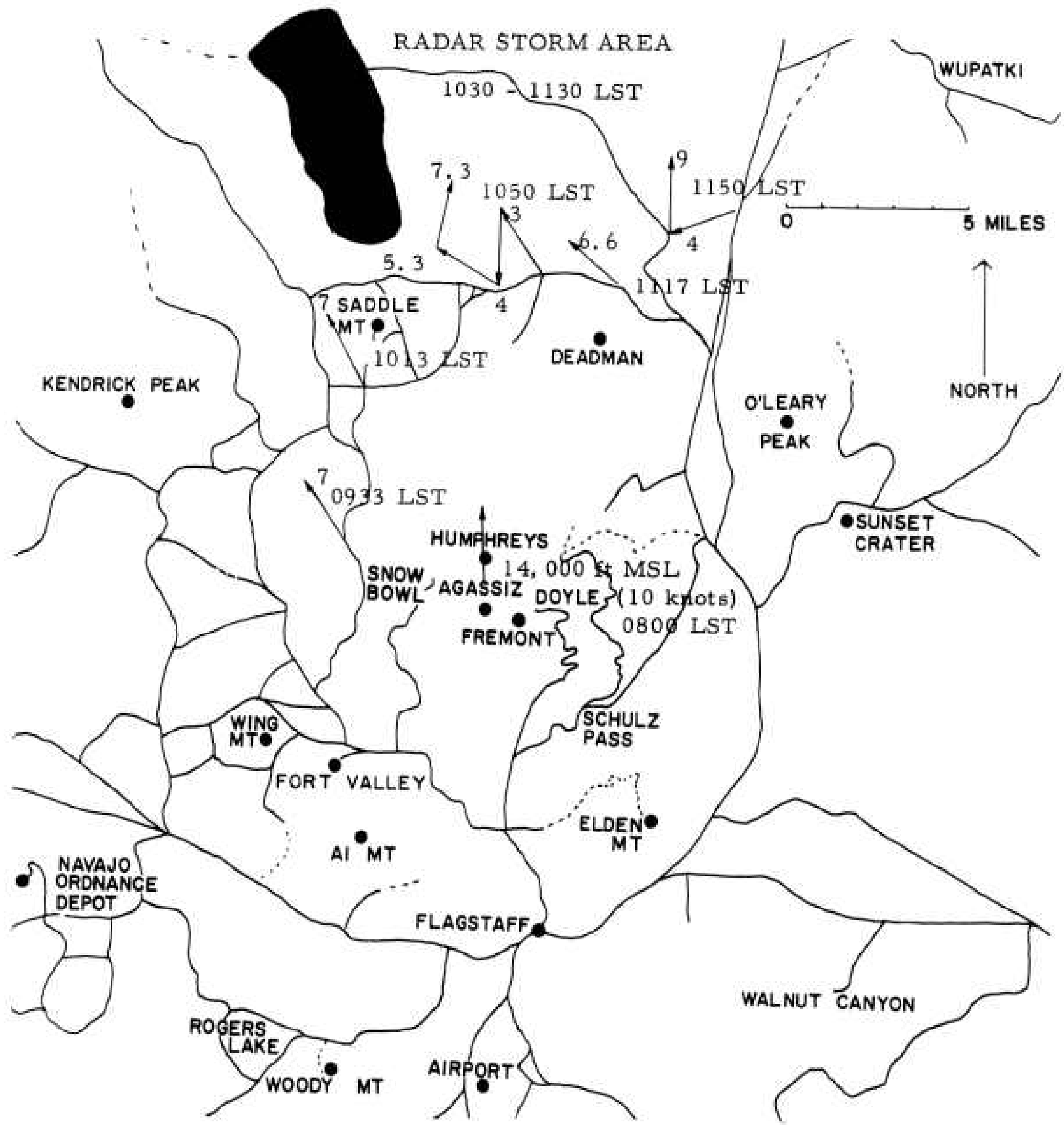


Fig. E-15. WIND DIRECTIONS AS OBTAINED FROM SINGLE THEODOLITE PIBALS TAKEN TO THE LEE OF THE PEAKS ON 9 AUGUST 1963.

Height (thousands of ft) to which the pibal rose in each stage of the run is shown at each arrowhead. The observation at Humphreys Peak is taken from the 0800 LST radiosonde run originating at Navajo Ordnance Depot.

patterns were found by Halitsky (1961) in a study of winds and turbulence in the wake of Bear Mountain. He noted considerable similarity between the observed converging surface flow and the flow field with a closed "bubble" behind a flat plate placed crosswind in an airstream.

Very favorable temperature conditions for isolated, long-duration wake storms are illustrated for 8 August 1963 in Fig. E-16. The approximate environment sounding for the time of initiation of the storm (about 1130 LST) has been constructed from the 0800 radiosonde observation at Flagstaff and the estimated surface temperature at 1130. The sounding shows little convective instability for parcel ascent and a convectively stable regime if entrainment is considered. This sounding apparently applied to the regions outside the wake since little or no storm activity developed. Within the wake region a major storm area developed with cloud tops estimated at 35,000 feet. It is conjectured that a modification of the environmental conditions must have occurred within the wake region which brought about additional convective instability and permitted generation of the large storm area. This modification, it is believed, resulted from the convergent flow in the wake and the mechanical lifting of the lower layers with subsequent increases in convective instability.

Convective wakes have been observed with wind coming from various directions, placing the wakes sometimes over rising ground and sometimes over descending ground. Therefore apparently the existence of the convective wake does not depend on the terrain surrounding the isolated peak. The precipitation regimes depend on other factors as well as the convective wake.

In the Flagstaff area in summer the precipitation average is greater on the higher land to the northwest of the peaks than on the lower land to the northeast, and there is much more vegetation to the northwest than to the northeast. The air coming from the southeast tends to be much moister than the air moving from the southwest. The extra precipitation to the northwest may involve the several factors of the convective wake, the rise of the terrain in that direction, and the greater moisture associated with southeast winds.

In summary, the observations of the wake storm development suggest that a major cause of the storm generation is the convergent flow in the surface layers behind the Peaks. The observations do not exclude, however, that wave effects may exert a minor influence on the wake storm and may, in some cases, serve to amplify the surface convergence effects.

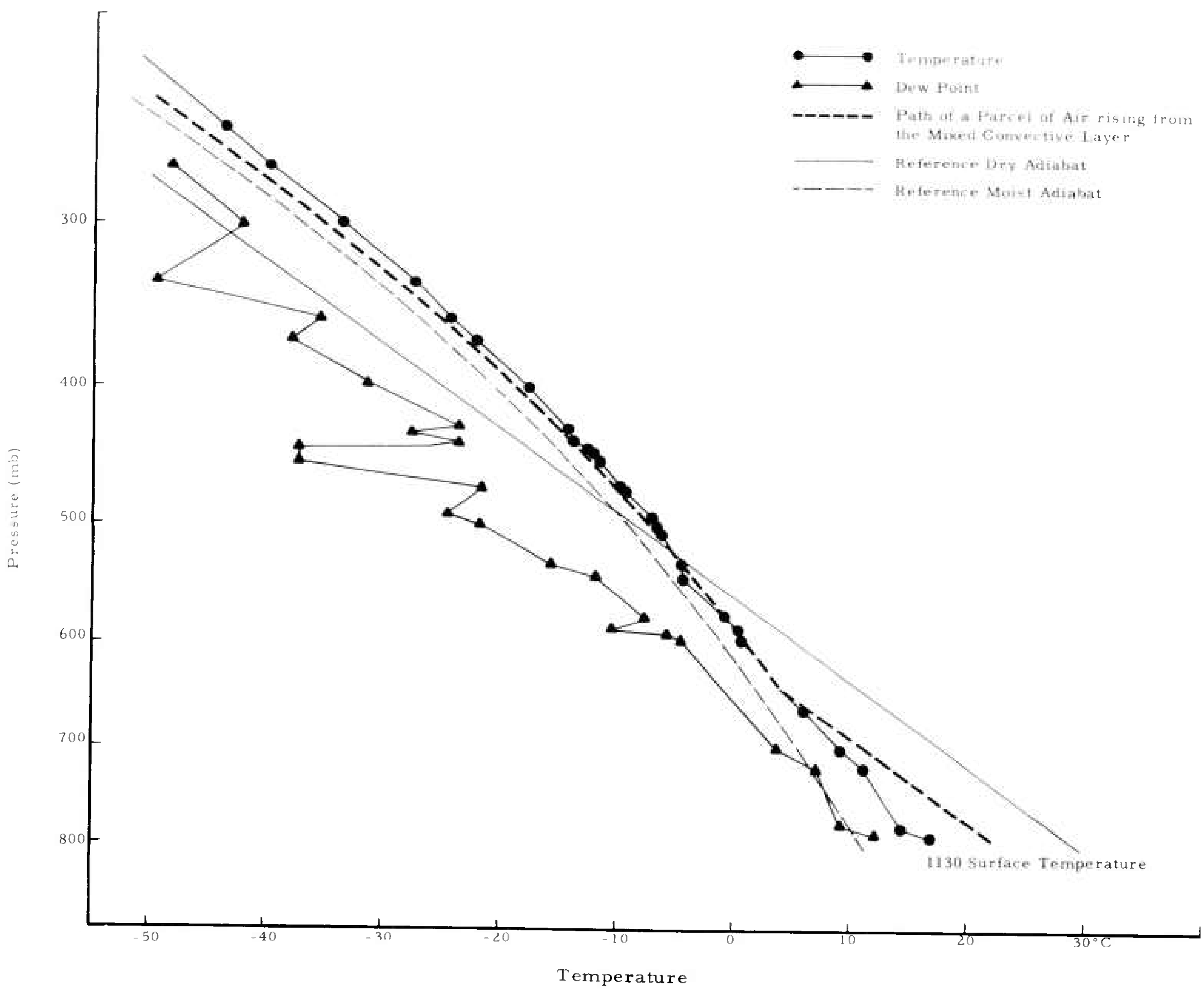


Fig. E-16. TEMPERATURE SOUNDINGS TAKEN AT 0800 LST ON 9 AUGUST 1963.

Conclusions

It has been shown that various cloud effects can be observed in the lee of an isolated peak. These effects can be related to the flow patterns which are considered to be typical of wave flow over ridges. Although the wave effects of the isolated peak are expected to be smaller than observed behind a ridge, the observations suggest that similar flow patterns may be recognized.

In addition to the wave effects on cloud development, a major storm area frequently develops in the lee of the San Francisco Peaks. The mechanism for its development requires the presence of a substantial convergence area in the surface layers in the wake of the Peaks. Although the wave flow over the Peaks may contribute to the development and location of the wake storm area and the slightly elevated terrain to the northwest may aid storms forming under southeasterly flow by providing a weak higher level heat source, it is believed that air flowing around the mountain in the surface layers and converging in the lee of the Peak is the major contributing factor in the development of the wake storm.

Under appropriate conditions of moisture, temperature and wind the wake storm may be the only precipitation area in the Flagstaff region. Under more moist conditions, the wake storm may form before other precipitation areas but as subsequent storms develop outside the wake, the airflow pattern around the Peaks becomes disorganized and the wake storm dissipates. Under moist conditions, precipitation may occur almost simultaneously at many locations and the wake effect may be obscured. With very light winds, no mountain wake exists and the heated slopes form the major storm generating influence.

The isolated nature of the wake storm and occasional long durations indicate a well-organized convective storm system. This, in turn, offers a unique opportunity for controlled experimentation on the modification of a major storm. Sufficient repetition in the storm development occurs from one hour to the next or from one day to the next to substantially reduce the natural variability to the point where seeding effects would become much more apparent.

F. Radar Angel Study

Introduction

At Flagstaff the M-33 radar regularly picked up strong radar angel echoes. The summer of 1963 was particularly good for observing angels since July was a very dry month and only rarely were potential radar angels obscured by precipitation echoes.

The frequency and strength of the angels had not been anticipated prior to the field program and the program was not set up to include a proper systematic study of angels. However, sufficient data were accumulated to provide several interesting points pertaining to these particular Flagstaff summer angels:

1) Surface conditions favorable for angel activity are high temperature, low relative humidity and moderate wind speed. The activity shows a maximum about 1100 local time.

2) Angels very often move from a direction more than 45 degrees different from the surface and upper level winds.

3) Potential temperature increases from 0.4C to 0.8C through an angel.

Plank (1956) distinguished three different types of radar angels according to their sources. There is reason to believe at least two different types were observed in the present study.

Angel Activity Related to Meteorological Parameters

In an effort to ascertain the dependency of angel activity upon various meteorological parameters, hourly observations of surface temperature, relative humidity, wind speed and cloud cover were tabulated with the simultaneous angel activity. The activity during each hour of operating time was rated excellent, good, fair or poor. The poor category included periods when the angels were nonexistent. The histograms shown in Fig. F-1 were constructed from these data.

The diurnal variation of angel activity is biased as no radar data were collected during the hours from 1900-0700 MST. During the daylight hours there is a maximum of activity around 1100 and a minimum toward late afternoon and evening.

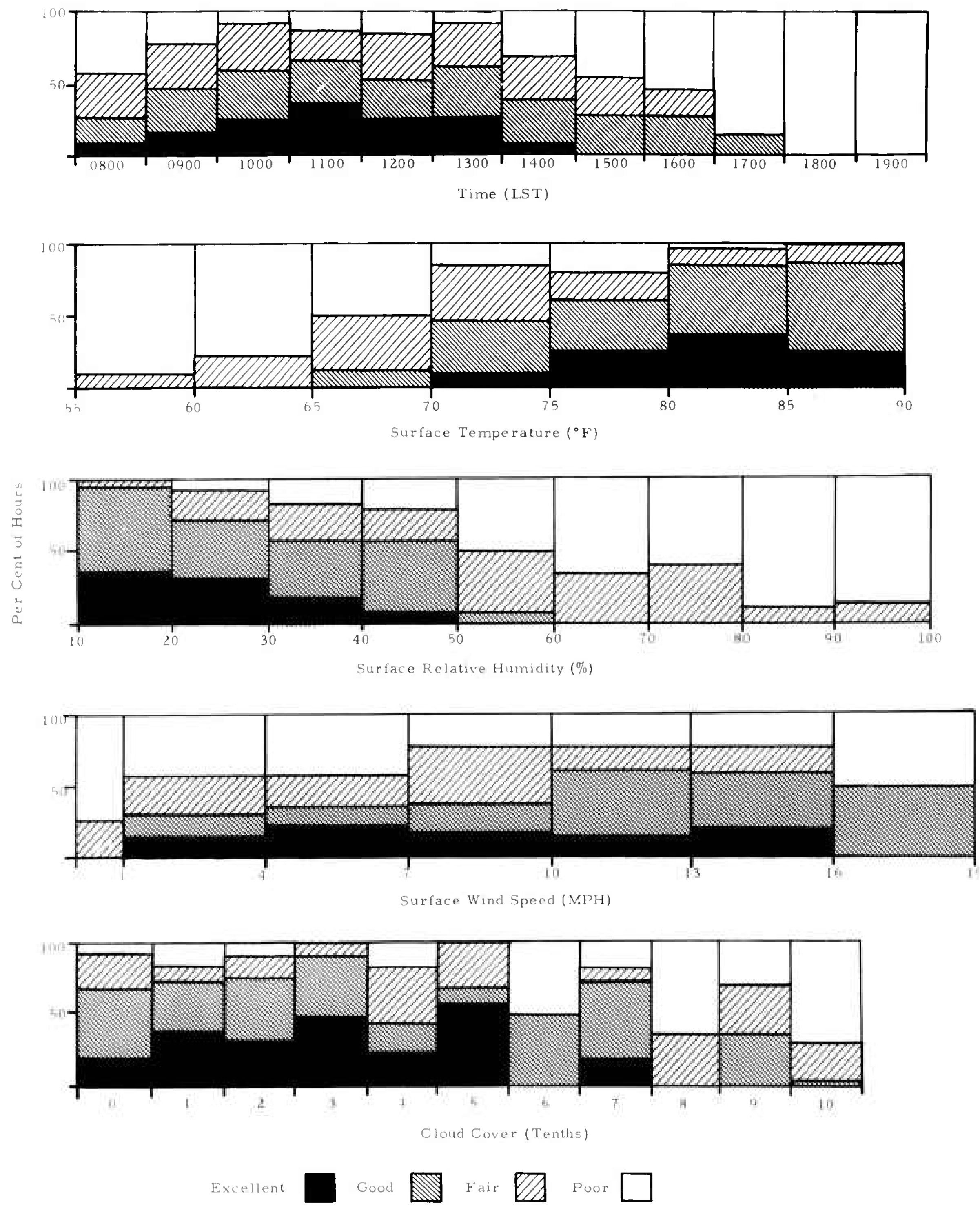


Fig. F-1. HISTOGRAMS OF ANGEL ACTIVITY VS. VARIOUS PARAMETERS

The clearest relationship between the parameters and angel activity is shown in the histograms of surface temperature and relative humidity. It can be seen that maximum activity occurs with high temperature and low relative humidity. High temperature promotes thermal activity, and low environment humidity permits large mixing ratio gradients as surface air rises. Moderate wind speed also appears to be favorable, although the relationship is not as clear-cut. It is interesting to note that the conditions favorable for angel activity are similar to those favorable for thermals.

The final histogram shows the relationship between angel activity and cloud cover. The few days on which precipitation echoes obscured potential angels were eliminated from the study, so this is not the reason for the minimum in activity under overcast conditions. In this presentation the importance of solar heating and moisture are shown. Under dry conditions the sky remains clear, the ground is heated, warm dry thermals rise and large temperature and moisture inhomogeneities can exist. Under moist conditions rising thermals condense, a cloud cover is formed and further thermal activity is reduced.

Angel Movement

Several authors (Tillman, Ruskin, and Robinson, 1961; Roelofs, 1963; and others given by Plank, 1956) have shown a definite correlation between wind and angel movement. In an effort to determine if a similar relationship existed in the present data, angel trajectories were compared with surface and upper-level winds. Figure F-2 is an example of the results of this analysis for 26 July 1963. The angel and slow-lift balloon trajectories (as obtained from the M-33 radar track component) are taken for points 5 minutes apart. It is quite clear that the angels moved from the north and northwest while the wind, up to at least 20,000 feet, was from the south and southwest. The GMD winds agreed generally with the zero-lift balloon winds, with a shearing layer somewhat above the peaks. Relative to the air rather than the ground, the angels were moving toward the SSW at over 30 mph, and actually moving a bit upwind.

This type of great disagreement was found to exist on 7 of the 20 days in the study. On only 3 days did the angels move with the wind. On the remaining 10 days the wind and angel trajectories were sufficiently varied to make their relationship uncertain.

Horizontal Structure

On 29 July 1963 several aircraft traverses were made through radar angels. Figure F-3 shows the resulting potential temperature and altitude traces. The radar verified that the aircraft did pass through the angel

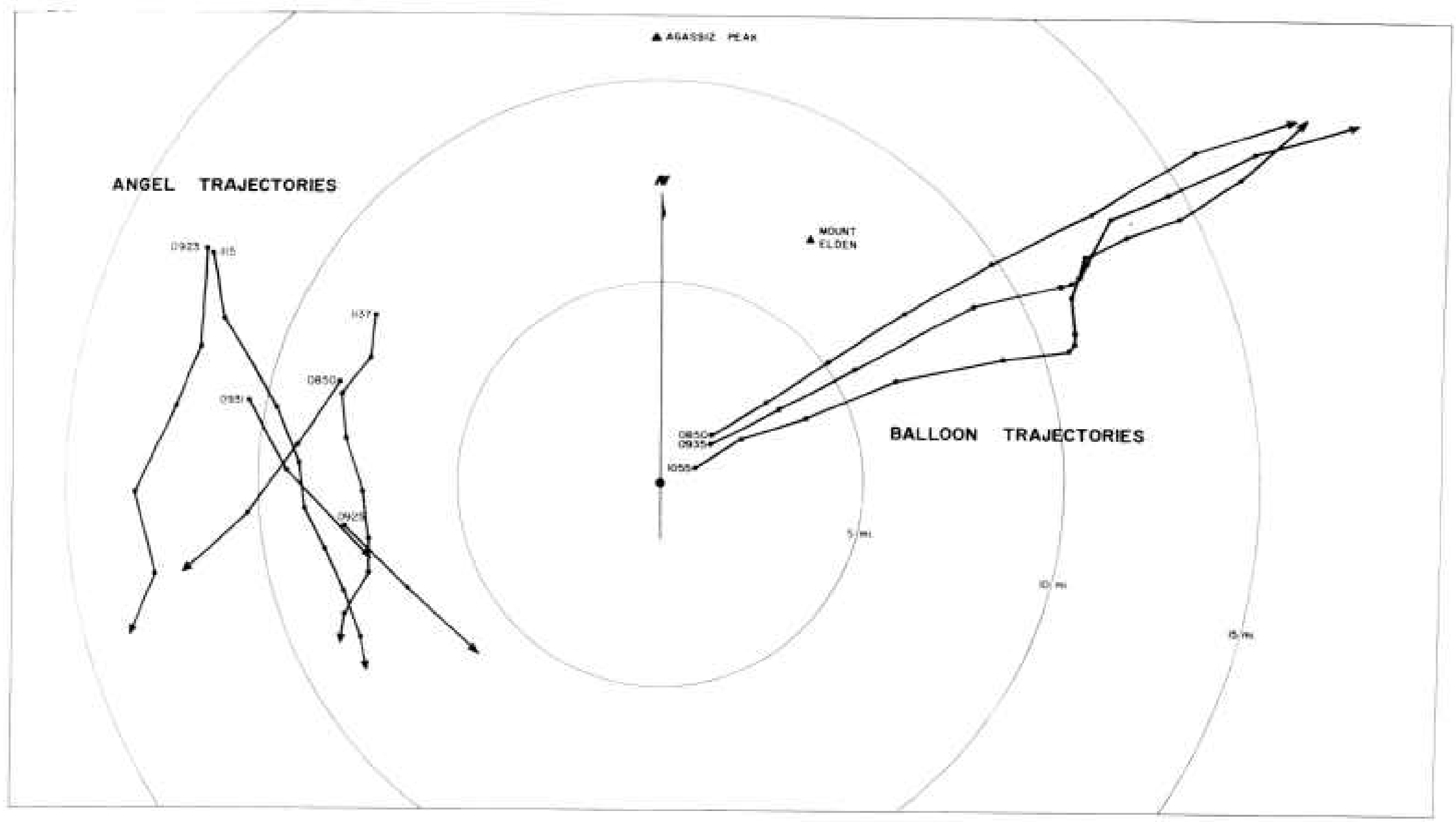


Fig F-2 ANGEL AND SLOW-LIFT BALLOON TRAJECTORIES FOR 26 JULY 1963. Points are spaced 5 minutes apart. Range markers at 5-nautical mile intervals.

(as observed on the 10 cm acquisition radar, which however does not have narrow height resolution). There is an indeterminacy of a few seconds between the records of the radar and the aircraft measurements, and so it is not possible in this case to specify on Fig. F-3 the exact time the aircraft was within the angel echo. Thus the angel timing indicated on Fig. F-3 is derived from the potential temperature-altitude traces, but in each case it coincides with the timing derived from the radar film within the small timing indeterminacy. In Fig. F-3, note the rise in potential temperature of from 0.4 to 0.8C and the lift often encountered by the craft as it passed through the angel. The aircraft was flying at approximately 120 mph and the diameter of the angels, as delineated by potential temperature, could be calculated at approximately 1000 feet.

On this day the angel movement was from the SW and the low altitude wind was also SW. At 14,000 feet the wind was W, and N at 23,000 feet. This day is considered as one of the 10 days with an uncertain relation between the wind and angel trajectories, since the "uncertain" category was rather strictly defined. Actually, these angels apparently did move with the wind and thus may be expected to relate to thermals as suggested by Fig. F-3.

Qualitative pilot observations during the radar echo hunting were that a fair correlation existed between an upcurrent and the M-33 showing the aircraft to be in an echo, but that many upcurrents were not observable as angel echoes and some angel echoes were in air without any special vertical velocity.

Summary and Conclusions

Insufficient angel observations have been made to make any definite statements about them. However, sufficient observations have been made to raise some questions.

It appears that surface conditions favorable for thermal activity are also favorable for angel activity. In an offhand manner this may indicate that the angels were, indeed, thermals. This would be confirmed by the series of aircraft traverses, which indicated a rise in potential temperature and strong updrafts. On the other hand, the movement of the angels against the wind would indicate that their source is not wind-borne. This would tend to rule out thermals. No observations were made of unusual bird, insect, or aircraft movements on the days on which the angels moved against the wind; such sources are deemed unlikely.

There have been sufficient data collected to hint that two very different types of angels have been observed. The first are the simple wind-borne angels which quite likely could be thermals. The second type is still unknown, but the fact that they move so differently from the surface and upper-level winds makes it appear that they are either not wind-borne or are involved in some type of complicated moving phase thermal or reciprocal path phenomenon. This peculiar angel movement is definitely a source for further study.

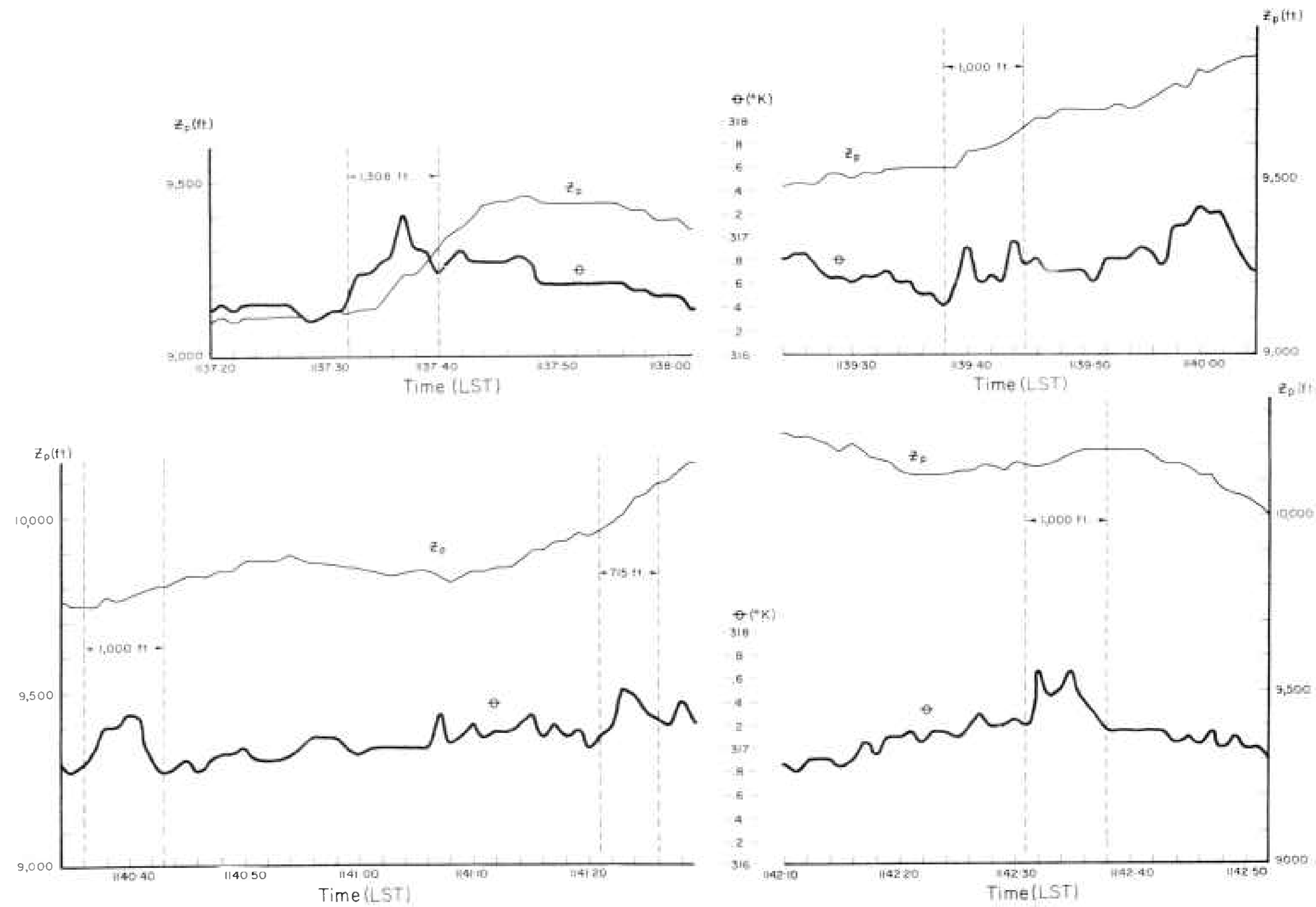


Fig. F-3. POTENTIAL TEMPERATURE AND PRESSURE-ALTITUDE VARIATION OBTAINED FROM AIRCRAFT TRACES THROUGH ANGELS ON 29 JULY 1963.

G. Undiluted Cloud Cores

The central strongly rising core of a cumulus cloud is the volume in which much of the development of hydrometeors and electrification occurs. Thus the exact amount of liquid water content available there is of considerable importance. For a short distance above the cloud base the value should be close to the theoretical value derived from lifting parcel theory. The question then is how high up the parcel rises before mixing from the edges begins to dilute it appreciably. This question is of course a vital one for cloud dynamics models as well as for cloud microphysics.

Corrsin and Uberoi (1950) performed experiments on the flow and heat transfer for a turbulent jet. Adapting their data to the cloud mixing problem gives the implication that some unmixed air should be found up to a height of about 4 base-diameters above the base. For cloud cells with upcurrents big enough to spiral in, say, 1 km diameter, this would imply a 4 km range of the unmixed core. In actual practioe it has proven difficult to find such large smooth upcurrents at cloud base, but not too difficult to locate them well up in the cloud. Thus the analogy between the atmospheric cumulus and the laboratory jet is probably not very close in this phenomenon.

A search for undiluted cores was made through flight data that had been analyzed on the Flagstaff cumulus cloud studies. The undiluted core was recognized when the updraft was nearly steady for several seconds of traverse, the temperature was relatively high and steady and the liquid water content was at a steady maximum. The duration and the height of these above the reference cloud base is recorded and plotted in Fig. G-1 against the width of the visual cloud at the height of the aircraft penetration. This chart shows that undiluted parcel ascent exists in columns of about 500 meters wide as much as 2000 meters above cloud base. These may be nearly 1/2 the visual cloud width at the level at which they are observed, or they may be only 1/10 the cloud diameter. An undiluted core even higher is discussed in Chapter I.

It has previously been noted in connection with earlier Flagstaff studies that homogeneous areas inside cumulus cores tended to be on the order of 300 meters in size. Further investigation has shown that typically the liquid water content is steadier than vertical velocity measured during traverses. The steady liquid water content best defines the unmixed region, and is often larger than the 300 meters.

It has been observed that often the cloud bases are a bit ragged. The unmixed core well up within the cloud would have characteristics

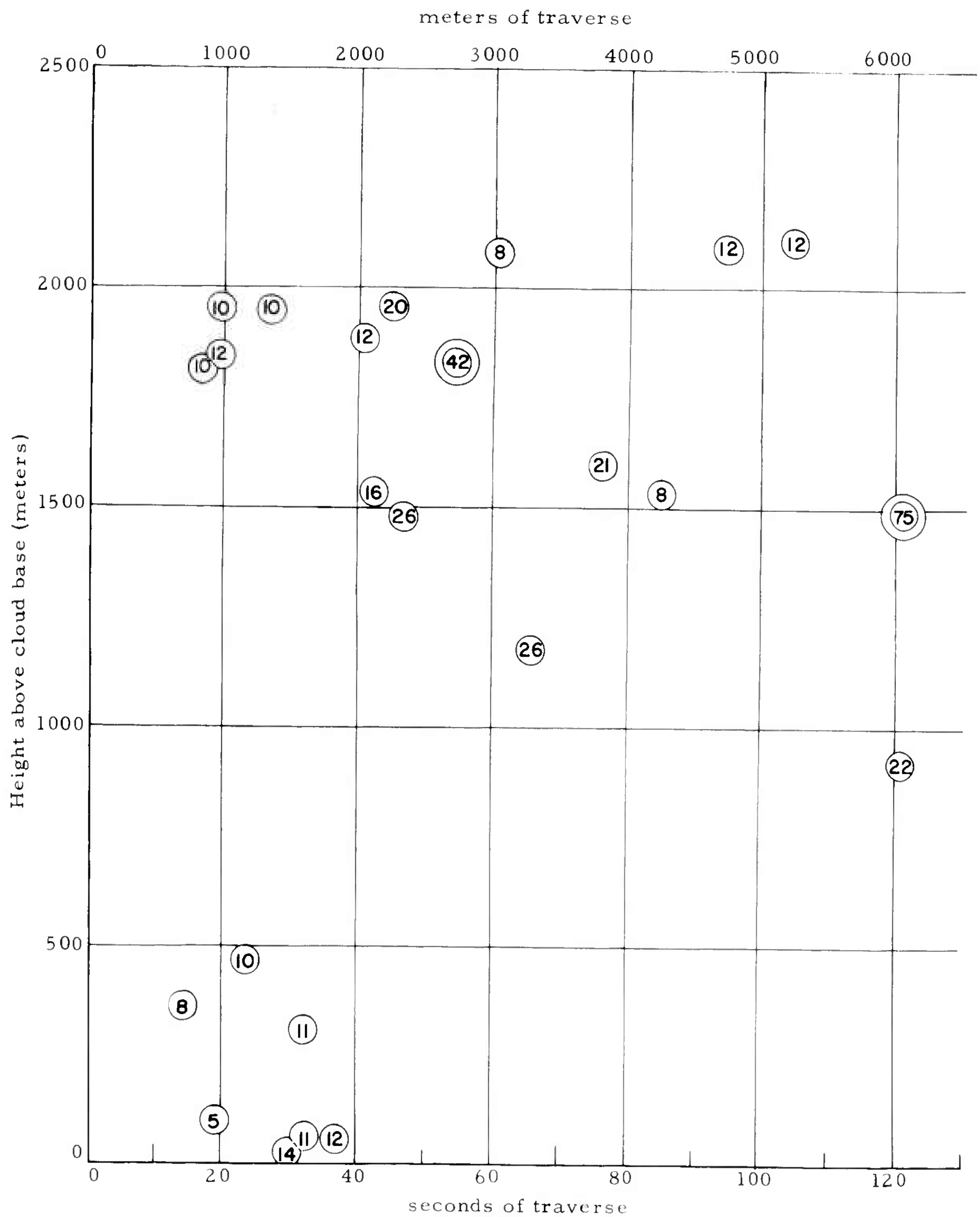


Fig. G-1. UNDILUTED CORES.

Numbers in circles denote seconds of traverse during which unmixed core was observed. Double circles represent spirals rather than straight traverses.

related to an effective cloud base which averages the condensation level of air entering the cloud. The visual cloud base, on the other hand, is usually ascribed to the lowest levels since the observer is looking at the base from a shallow angle. The discrepancy between observed and effective cloud bases tends to be smaller for the higher altitude bases, because there is more time and distance for the core air to become mixed before condensation occurs.

H. Investigations of Cloud Droplet Concentration

Rapid Coalescence

Droplet spectra have been measured for a particularly good example of continuous sampler record: the spiral up into a cold seeded cloud (base -9.5C, upcurrent 5 m/s) on 15 August 1962. This case has already been examined in a study of quantitative ice crystal growth (see Todd, 1963) and the sampler record used as an example in the report on the continuous sampler (MacCready and Todd, 1964, reviewed here in Chapter D).

Fig. H-1 gives 12 droplet size spectra covering a height range from cloud base to 680 m above the base. For convenience the spectra are given in terms of replica diameters rather than droplet diameters. The approximate calibration factor relating droplet diameter to replica diameter can be derived from Fig. D-2 assuming a dry Formvar film thickness of 3 μ for the 1 per cent Formvar solution used. Using this factor gives approximately the correct total liquid water content value for an unmixed cloud at the level where the size spectrum and concentration is made. The collection efficiency factor used for Fig. H-1 is based on replica size rather than droplet size, but the error caused by this is small compared to the overall variations of the data.

It is of interest to note the narrowness of the distributions on Fig. H-1. At cloud base it is particularly narrow, but by the fifth sample,and possibly on the fourth, there is an indication that there are some droplets appearing beyond the expected range on the large end of the distribution. These are of a size such that they could be made up of a coalescence either of two or three of the droplets.

Column B of Fig. H-1 gives the total number of droplets per cc as computed from the integrated spectra. This number is around 1150/cc in the bottom 20 meters, but quickly decreases. Column A gives for each level the estimate of the number of particles which would have been there before coalescence; this number decreases only slowly with altitude (a 6 per cent decrease is expected because of the expansion of the rising air). The most direct interpretation of these data is that droplets are coalescing in the cloud rather effectively when all are even smaller than 10 μ . Experience with the sampler leads one to believe that it is unlikely that the coalescence could occur in the replication process on the film.

A. Concentration cm^{-3} corrected to estimated number before coalescence.
B. Concentration cm^{-3}.
C. Height above cloud base in meters.

15 August 1962

A	1090	1240	1140	795	840	810	1150	1050		920	850	
B	1090	1240	1140	780	690	700	870	850	740	770	520	450
C	0 (CB)	12	20	32	80	130	254	282	382	433	620	680

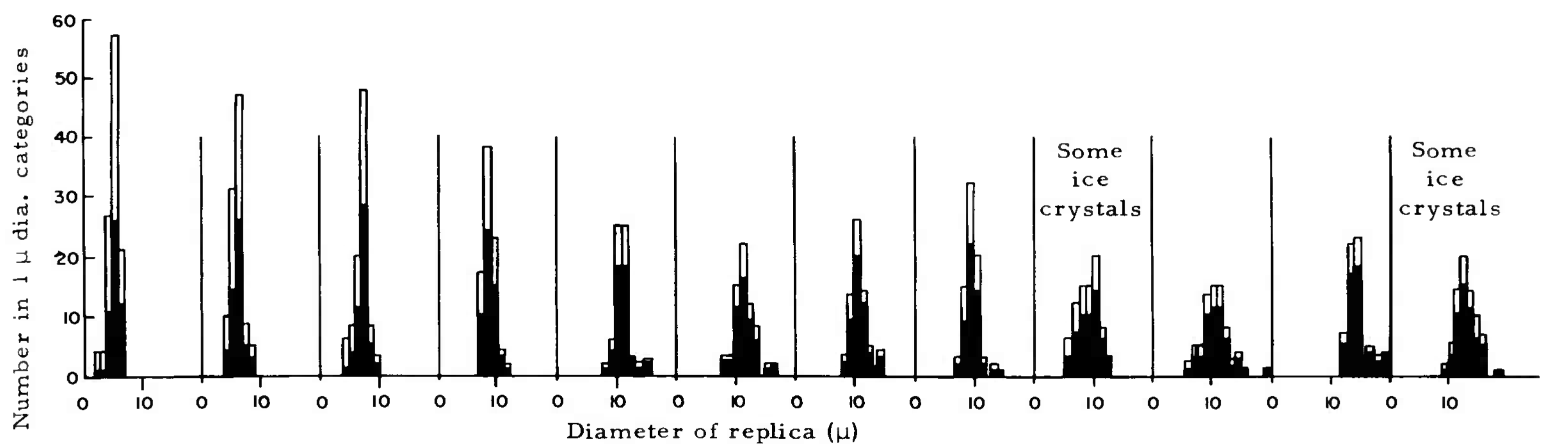


Fig. H-1. DROPLET SIZE SPECTRA.

These spectra were taken in a spiral flight up through the base of an active cumulus cloud. The dark line graphs represent a sample of 50 droplets that were measured. The open bars represent the count increased by the reciprocal of the collection efficiency. For each distribution the height above cloud base and the concentration per cm^3 is listed.

The apparent rapid coalescence is not in accord with classical theory on the subject. According to the theory of droplet collision from aerodynamic forces as developed by Hocking (1959) and Shafrir and Neiburger (1963), the largest droplets would have to be nearly 3.5 times their present diameter to be able to collect any cloud droplets. One factor which can improve the coalescence situation is the altitude effect; droplet speeds are considerably greater at the 6500 meter altitudes involved than they would be in the sea level conditions for which the theories are developed. Another very important factor may be related to electrification. A seeded cloud on this day did show strong negative charges on some graupel pellets at high altitude, and even much weaker electrification can be expected to have an effect on early coalescence. Recent work by Dr. M. H. Davis of the Rand Corporation (not yet published) shows that there can be an 0.5 collection efficiency between a drop of 10 μ and a droplet of 9 μ diameter if the larger drop carries a charge and the smaller one has no charge. The charge need be only 1×10^{-7} esu on a 10 μ diameter drop, which is the range that Twomey (1956) reported. The charge makes the collision possible where the aerodynamic force does not because there is a long time of about 1/2 second when the droplets pass each other in which a small electrostatic force can have an important effect.

Cloud Base Droplet Concentration Vs. Upcurrent Strength

According to theory (Howell, 1949; Mordy, 1959; Neiburger and Chien, 1960), the cloud droplet concentration in the undiluted portion of a cumulus cloud is determined in the first 100 meters or so above cloud base. The concentration is a function of the rate water vapor is made available for condensation, and the concentration and size distribution of condensation nuclei. The rate that the water vapor is made available is a function of the rate of updraft, the temperature, and the density of the air. None of the published treatments cover the cloud base updraft rate observed in summer cumulus at Flagstaff, 2 to 20 m sec^{-1}. The fastest updraft rate considered in the literature is 1 m sec^{-1}.

A quick check to see if the rate of updraft has any gross effect on the droplet concentration was made by plotting the droplet count on the replica record with the rate of updraft observed in the undiluted cores of the cloud updrafts. From this plot it was apparent that the differences in droplet counts from day to day and from upcurrent to upcurrent are larger than the differences that appear to be associated with change in the updraft velocity.

Since no gross effect was apparent, checking for the existence of a correlation between the droplet concentration and upcurrent strength requires a rather more refined data reduction procedure than was employed here. To get accurate concentrations the replica sizes must be corrected to true droplet diameter, and the collection efficiency factors must be applied to each diameter range. Then the problem remains to estimate the concentration which existed at cloud base. The concentration of droplets has been shown in this chapter (and will be shown also in Chapter I) to decrease rather rapidly with height, presumably because of coalescence. Thus the height of measurement above cloud base apparently has a strong influence on the droplet concentration, an influence which manifests itself appreciably well before the air has ascended 100 meters into the cloud.

I. Liquid Drop Growth

General

On many occasions during cloud traverses in the 1962 and 1963 field seasons the flight observer reported the occurrence of small drops (300 to 1000 μ diameter) which impacted on the windshield. The drops were generally associated with a strongly rising core of the cloud, although not necessarily identified with the point of maximum upcurrent. The drops were encountered even within rather small clouds, and at temperatures both above and below freezing. On other occasions these droplets were not found.

Thus it appeared that an efficient warm cloud mechanism was sometimes in operation at Flagstaff. One series of cloud penetrations proved particularly effective in illuminating the details of the process: the 1445-1513 LST portion of a general research flight on 2 August 1963. The continuous sampler operated well on this flight until the window slot iced over due to insufficient heating at 19,500 feet and a temperature of -6C. Although there was flocculation at the colder temperatures the replica sizes and counts were still significant. This flight provided information on the operation of the sampler, namely showing the effect of large (considerably greater than 50 μ diameter) drops.

At a temperature of -5 or -6C ice particles were found in the strong upcurrent. Because of the strength of the upcurrent, and the fact that the particle sizes were comparable to those of the water droplets at lower altitudes in the upcurrent, it seems unlikely that these ice particles had fallen from colder regions. The most direct explanation is that these particles represented frozen drops which were riming, and had frozen in the 1-1/2 to 2 minutes during which they had traversed the region from 0C to -5C. This effect is the same as that described by Koenig (1963), pertaining to summer cumulus clouds in Missouri.

At the time of the flight there was precipitation and lightning from convective clouds in the area. An attempt was made to spiral up within a single upcurrent, but this was not successful because the upcurrents as found did not seem large enough and were particularly ill-defined and weak at the lower elevations. Therefore a composite picture was compiled consisting of traverses and partial spirals at increasing altitudes through several clouds in the same general area.

The data used in this analysis are all taken from the aircraft temperature, pressure in terms of a standard atmosphere altimeter, liquid water content, the continuous particle sampler, and the observer flight notes. The various data all combine to give a reasonably consistent picture. There are some inconsistencies due to the crudeness of the data and its

reduction, and to the fact that features of several cells are incorporated into one case, but nevertheless the main points do seem to fit into a reasonable and rather simple physical picture.

The Continuous Sampler Record

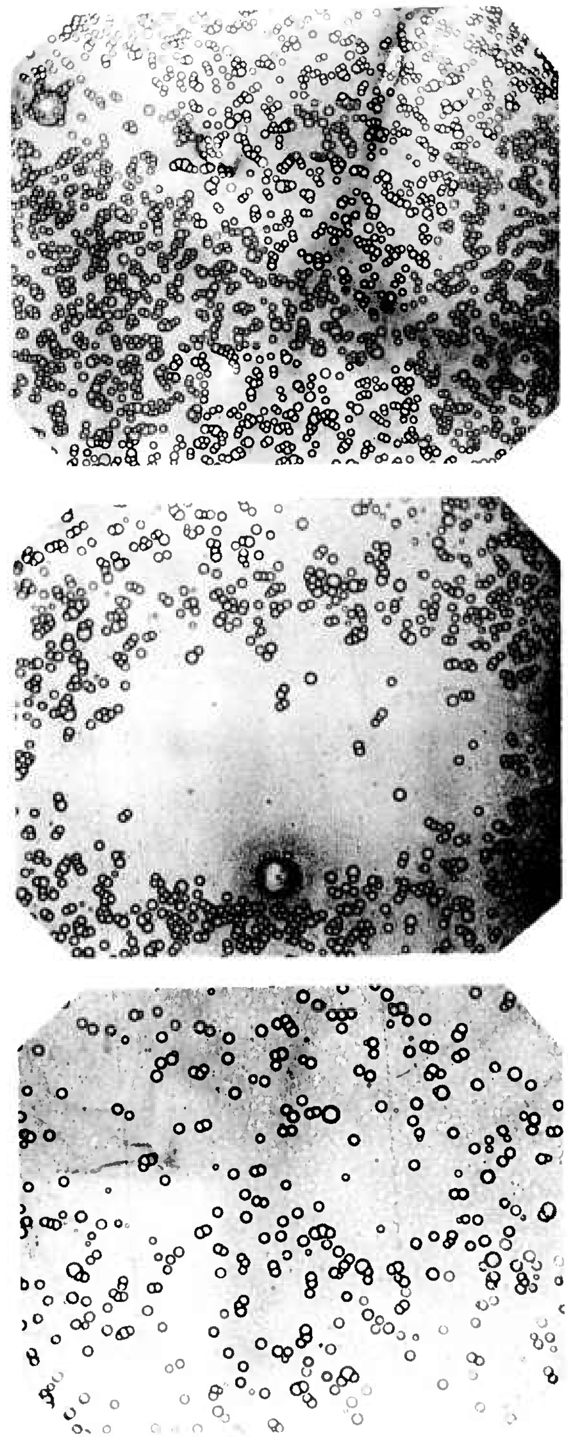
The details of the sampler as used on this project are contained in Chapter D. For this flight the sampler used a 2.5 per cent solution of a mixture of 25 per cent $CH\ Cl_3$ and 75 per cent $C_2H_4Cl_2$. The relation between image size and original droplet size is taken from Fig. D-2, with the assumption of a final dry thickness of Formvar of 7 μ (derived from laboratory measurements of 10 μ dry thickness for a 3.5 per cent solution applied with a similar coating wheel). Collection efficiency was estimated from Fig. D-3 with a small correction arising from the aircraft speed actually being about 60 m/s rather than the 50 m/s used in deriving the curve. Flocculation was encountered at the temperatures below 0C, but the droplet concentrations and approximate sizes could still be found until the window slot iced over in a dense cloud at -6C.

The sampler is ordinarily considered to give information only concerning small droplets, say up to 30 or 40 μ diameter, because, at these flight speeds, larger droplets would be expected to break up. The sampler records were examined for those portions of the film where the observer had noted "half-millimeter droplets" hitting the windshield, and large clear areas were found on the film, each with a large droplet residue remaining at one edge of the cleared area. It is believed that these cleared spots (see Fig. I-1) represent the impact of drizzle-size drops. The size of the cleared area should be somewhat related to (but larger than) the size of the impacting drop; the size of the remaining circular residue (70 to 400 μ) probably depends on minute details of the splash and so is not well correlated with the drop size. The droplet spectrum outside the cleared area is apparently not particularly altered by the splash. Replicas in the 70-100 μ diameter range without an accompanying splash area are assumed to represent ordinary large droplets (of 36-46 μ diameter, using the standard correction of replica to droplet size).

The Case Study

Figure I-2 contains six parts which summarize the pertinent data obtained on the flight.

Figure I-2a gives the temperature measured by the vortex thermometer in the strong upcurrents and also outside the upcurrent areas. The solid line is a wet-pseudoadiabat. The environment temperature shows increasing instability with height. The sounding taken at Flagstaff at noon had a weak stable layer at 21,000 feet pressure altitude, and dryness above that point.



a. 13,100 ft, in 1000 ft/min upcurrent. 100 μ dia. replica presumed to be unbroken droplet, but slightly cleared areas around it may indicate it is residue of a somewhat larger droplet.

b. 14,600 ft, at edge of weak upcurrent. Shows 700 x 1100 μ cleared area, with 115 μ dia. residue droplet, presumed to result from impact of a 500 to 1000 μ dia. drop.

c. Replicas at 16,700 ft. Low concentrations at edge of cloud (same spectrum as in dense cloud core where flocculation occurs).

Fig. I-1. EXAMPLES OF CONTINUOUS SAMPLER RECORD, 2 AUGUST 1963.

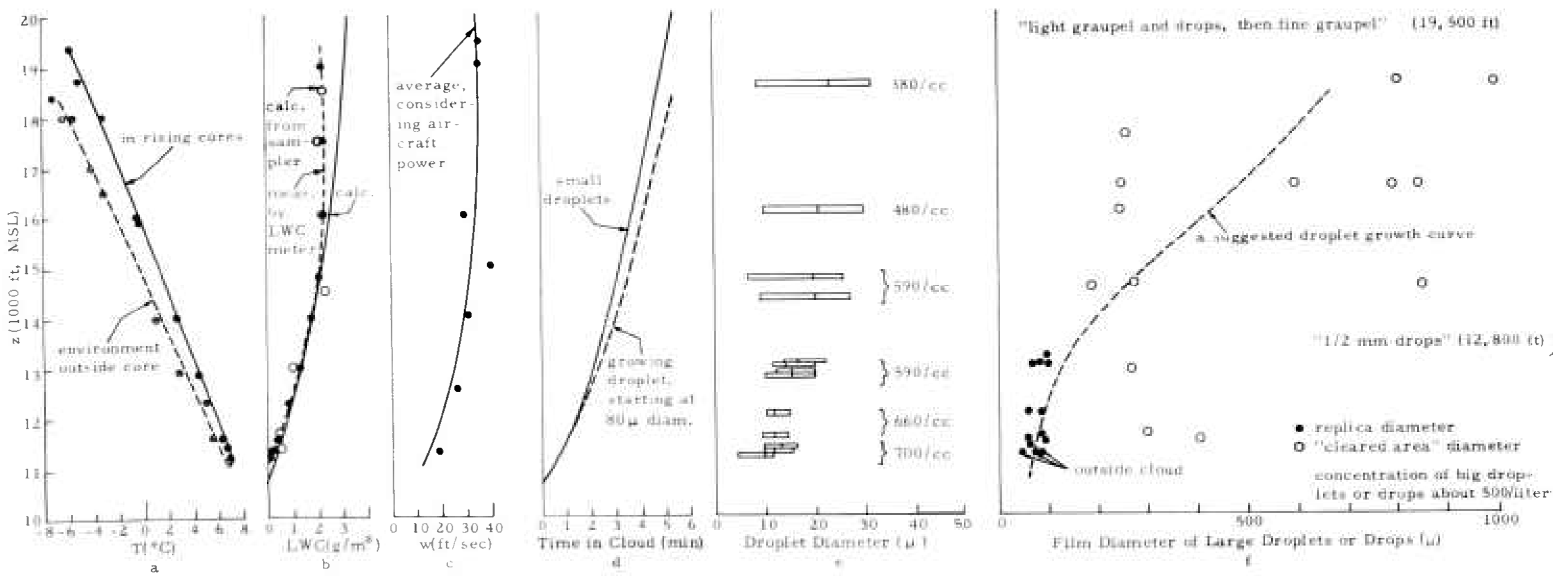


Fig. I-2. SUMMARY OF THE GROWTH OF DROPLETS, 2 AUGUST 1963.

As evidenced by the existence of strong precipitation and hail, the large convection cells carried well above the flight altitude.

Figure I.-2b gives the theoretical liquid water content (LWC) in gm/m^3 based on a parcel rising from a cloud base at 10,600 feet. The bases were spotty, and varied somewhat in altitude with the lowest being about 10,400 feet. The measured points come from the Johnson-Williams hot wire LWC instrument. The absolute calibration of this device at these altitudes and air speeds had not been obtained, and so this curve has been adjusted by a constant value throughout so as to fit with the theoretical curve during the lower portions of the ascent. As the cloud droplets get large the ones colliding with the heated wire do not vaporize completely and the sensitivity of the sensor decreases. This presumably is part of the reason for the decrease in the measured value relative to the calculated one at high altitudes. The effect would be particularly evident as some of the droplets get very large by coalescence. In a crude way the difference between the measured and calculated values can be considered as representing the amount of water contained in the drizzle size drops, say well over 100 μ in size. The LWC instrument showed the upcurrent cores were rather smooth over dimensions of the order of 2000-3000 feet (the LWC values were smoother than the vertical velocities). The steady high LWC values always correlated with the upcurrents. The existence of the steady LWC values verifies that the cores were unmixed with drier outside air, even at the highest altitudes measured, 9000 feet above the base. The large circles on Fig. I-2b show the liquid water content estimated very roughly from the drop sizes and concentrations as obtained with the continuous sampler.

Figure I-2c depicts the vertical velocities in the upcurrent cores. The solid line is the averaged value taking into account the power setting of the aircraft and its speed and bank angle so as to account for the rate of rise of the aircraft relative to the air.

Figure I-2d is the integral of the rise rate of Fig. I-2c. Thus it shows the time-height curve followed by a parcel of air or by very small droplets. The dotted line represents the time-height curve for a droplet which has an initial diameter of 70 μ at cloud base and which grows by coalescence. Its growth and integrated fall distance are estimated, very roughly, from the calculations by MacCready (1959). After 5-1/2 minutes the drop has reached a size of about 1 mm diameter, but has only fallen less than 2000 feet relative to the ascending air and is still ascending rapidly. The relative descent of the large particles through the air parcel would distort the LWC curve of Fig. I-2b downward, but Fig. I-2d shows the magnitude of the effect would be very small for this strong upcurrent case.

Figure I-2e presents results from the small droplet measurements with the continuous sampler. The horizontal bars show the maximum and minimum sizes at each altitude (qualitatively representing the 2 per cent and 98 per cent distribution limits), and the mass average size. The numbers denote the concentration of droplets per cc. Those LWC values on Fig. I -2b derived from the sampler were obtained from these concentration numbers and the average sizes. The droplet concentration shows a definite decrease with altitude. The droplet number decreases with time as droplets coalesce and as droplets are swept out of the volume in question by falling drops. The growth of the droplets by condensation (to 15 μ) in the bottom thousand feet of the cloud seems barely able to permit coalescence to start, unless an improvement in collection efficiency can be assumed because of the potential gradient or droplet charges. There was a vertical potential gradient significantly larger than the fair weather field even at the lowest parts of the cloud. At all altitudes some 5 μ diameter droplets were encountered, which are not shown in Fig. I -2e.

Figure I -2f plots the data on very large droplets or drops, as ascertained from the flight observer notes and from the drop sampler. The solid dots indicate the replica diameters of large droplets. They show that some large droplets are present even in the lowest portions of the cloud, which implies that the droplets are attributable to large condensation nuclei. These large droplets were also found outside the base of the clouds, as would be expected for droplets from giant condensation nuclei. The large circles on Fig. I -2f represent the dimensions of the cleared areas on the sampler film which are considered to represent the impacting of drops of somewhat comparable but smaller size. They all left residues which were 70 to 190 μ in diameter (except for several cases of 400 μ diameter for the largest cleared areas). The dotted line is a sketch of the likely growth of a drop starting at 70 μ diameter at cloud base and growing by coalescence. This line represents true diameter, not the "cleared area" diameter on the film. This dotted line demonstrates that some of the drops can grow to the observed sizes within this cloud system. The line also suggests that the mass of the drop starts growing rapidly above 14, 500 feet, which is in agreement with the difference between the calculated and measured LWC curves on Fig. I --2b. The existence of sizable drops at lower altitudes may derive from the influx of larger condensation nuclei than assumed, and from the existence of slower upcurrent regions in the clouds than the peak upcurrents used here for analysis.

Large droplets were found outside the cloud at cloud base, and large droplets or drops were found virtually everywhere smoothly throughout the parts of the cloud with good upcurrents. The simplest explanation would seem to be that giant condensation nuclei were widespread in the surface air; without more measurements one cannot completely rule out

the possibility that the large droplets and drops grew over a long period of time by ordinary coalescence from small cloud droplets, and were entrained into the upcurrent. The concentration was on the order of 500 particles per liter. This concentration of drops would involve 1 gm/m^3 of water if the drops were about 160 μ in diameter; this is not inconsistent with the sort of "cleared area" sizes found on the film.

At the peak altitude studied, both drops and graupel were encountered, as noted by the observer. A rather unusual vortex motion system would have been required to bring the graupel into the upcurrent from higher altitudes without first entering a melting region. Therefore, it seems more reasonable that the graupel was derived from ascending drops, freezing at extremely warm temperatures as noted by Koenig (1963) from some mechanism not as yet understood. It is possible that the giant nuclei, which presumably initiated each of the frozen drops, somehow aided in the freezing process. There was still a great deal of supercooled water in the cloud, attested to by the heavy icing (described as "more glaze than rime" by the observer). Thus AgI or CO_2 seeding of such a cloud could still produce a dynamic heat-release effect, although seeding would not be needed for precipitation initiation.

J. Cumulus Internal Lateral Velocities

Rework of the M-33 radar electronics offers the possibility of recording the total true horizontal ground speed of the aircraft. This measurement, coupled with the true air speed measurement from the aircraft, can easily be combined to give the horizontal wind speed along the flight path.

This radar modification was attempted at Flagstaff. Preliminary tests with the technique made it seem to be feasible to use with a response time as short as 5 seconds. Because of the relatively slow response of the aircraft true ground speed to gusts or control maneuvers, this M-33 response time was felt to be sufficiently short to yield meaningful data for a carefully flown aircraft. On 10 August 1963, isolated cumulus clouds began developing in light wind conditions over the San Francisco Peaks. These seemed to offer a good opportunity to try the horizontal wind speed measuring technique. Various systematic aircraft penetrations were made through the cumulus towers, with the aircraft and radar records carefully coordinated. Due to various experimental difficulties the aircraft radar records did not manifest enough accuracy to be usable (although they had on a previous flight), but nevertheless the aircraft true air speed measurements are of value because the airplane was flown carefully and in a systematic manner.

Four brief sections of the flight results are shown on Fig. J-1. These were the only portions of the flight in which strong sustained upcurrents (> 15 ft/sec for 10 seconds) were noted and for which true air speed records are available (after the fourth event the true air speed propeller iced up). The cross sections were not of the same cloud.

The heights of the cloud tops were not known in these cases. Bases were about +6C and 11, 700 feet. The traverses were from 15, 000 to 16, 200 feet, at -1C to -4C. The visual tops were estimated to be several thousand feet above flight altitude. The upcurrents were encountered well within the cloud mass; the tops of the actual upcurrents studied thus would not necessarily coincide with the tops which had been visually seen before the aircraft entered the cloud mass.

All four of the cross sections demonstrate somewhat similar characteristics. The vertical velocity regime (taken from the altimeter records, corrected for time lag from aircraft response and instrument lag) was sharply delineated in the last three cross sections. The true air speed in every case showed some increase on entering the upcurrent and some decrease on leaving the upcurrent. In the first two cases the aircraft was slightly slowed by the pilot after entering the updraft; this effect plus the longitudinal response of the aircraft means the true velocity change must have been greater than that indicated on Fig. J-1. In summary, it seems reasonable to state that the data are consistent with an outflow around the updraft of the order of 15-20 feet per second, which is about comparable to the strength of the upcurrent.

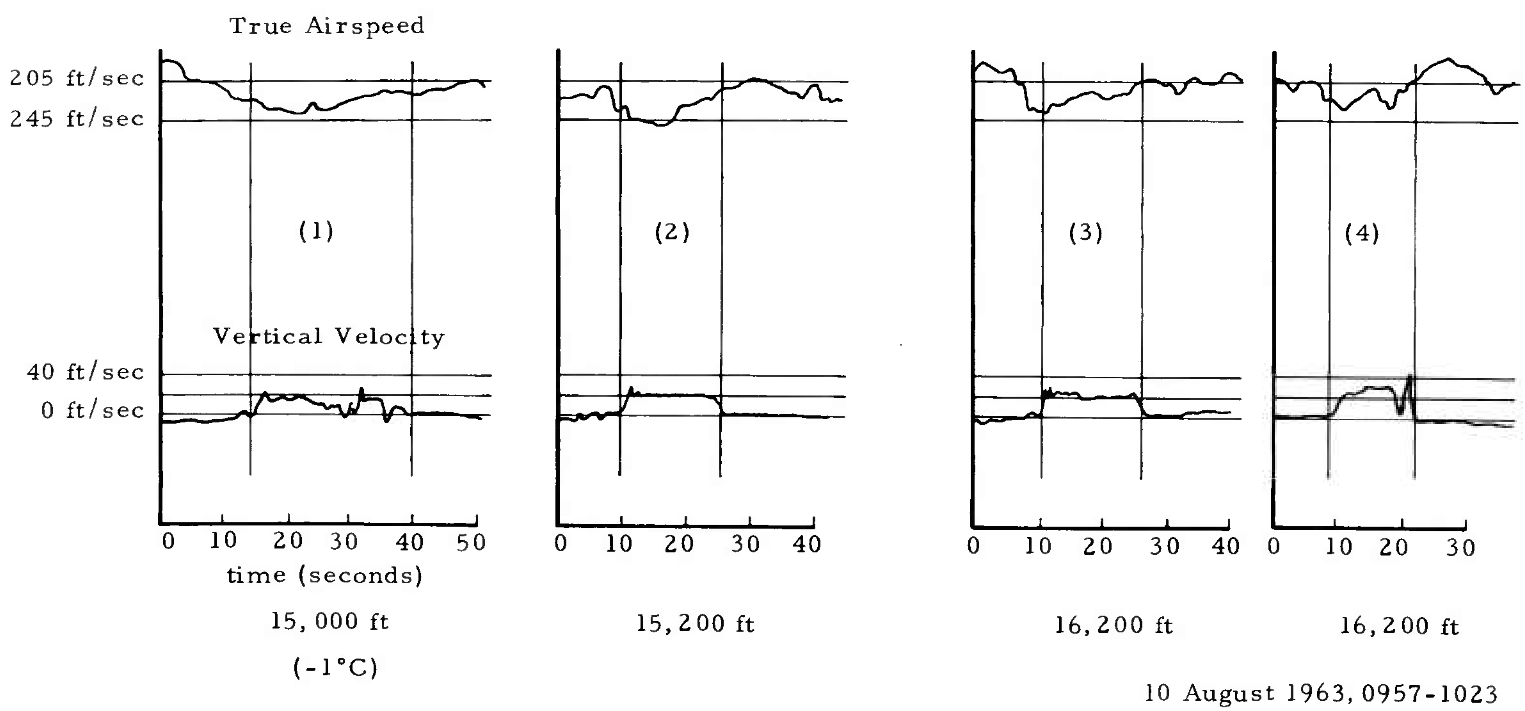


Fig. J-1. CLOUD CROSS SECTIONS.

The measurements are rather crude. They are presented here more to illustrate the technique than to answer cloud dynamics questions. The amount of indicated outflow is somewhat greater than one would have expected from models of the tops of thermal bubbles or the caps of thermal plumes (see Woodward, 1959, for cross-section data on a laboratory study; Turner, 1962, and Todd, 1964b, pertaining to the starting plume configuration in laboratory and field). The temperatures within these clouds were close to the outside temperatures, and so considering condensate weight the clouds had negative buoyancy at the altitude of measurement. If the clouds were pushing up through a relatively stable atmosphere, near the tops the lateral flows would be increased and the core upcurrent decreased.

The M-33, properly modified, should be able to make such studies feasible with more accuracy in the future. A preferable technique would be the use of doppler navigation radar to establish ground speed. Alternatively, with proper accelerometer and gyro instrumentation, the relative aircraft ground speed could be established without radar. The M-33 technique offers the most economical approach, although for strong, precipitating clouds, a radar beacon is needed on the aircraft.

K. July 29 - Example of Complete Coordinated Seeding Operation

Introduction

The operation on this day provided a good example of a complete coordinated seeding investigation. Nature was cooperative in creating supercooled clouds limited by a strong inversion so that no natural nucleation was occurring in the area and any artificial seeding would be distinctive. Photographs from the ground showed the effects. The 10 cm acquisition radar of the M-33 simultaneously showed the Cessna seeding plane, the Apache research plane, and the development of the artificial echo. The tracking radar plotted the positions of the aircraft and by radio the research aircraft could be vectored through the area of interest. The research aircraft operated systematically and obtained good droplet and crystal samples together with records of altitude, temperature, turbulence, airplane charge, and potential gradient, and observers notes. Especially useful comparison data were obtained by flying through an unseeded cell immediately after traversing a seeded cell.

The cloud situation precluded getting any economically useful results from the cloud. The virga from the seeding evaporated well before reaching the ground. The clouds were so thin, and against such a strong inversion, that no net increase in vertical rise could accrue from the seeding.

The Natural Environment

The sounding for the afternoon of July 29, 1963, showed a strong inversion of 4C at 460 mb (a pressure altitude of 20, 200 feet, and a true altitude about two thousand feet higher). The research aircraft measurements were consistent with the sounding and gave cloud base at 17, 550 feet at -7. 5C, and a few tops just reaching 20, 500 feet. Temperature in the core of a high top at 20, 200 feet reached -13C. The clouds were sufficiently limited so no natural glaciation was observed in the area. The wind was very light from the west at the lower altitudes and from the south at cloud altitudes. As shown by the lack of drift of the seeded echo, the wind was extremely light. Figure K-la shows the cloud situation 12 minutes after the start of seeding but before any definite visual or radar effects had become evident.

The Seeding

The Cessna 180 went aloft with Alecto pyrotechnic AgI generators and the Fuquay type acetone AgI generators. Due to some electrical

a. 1615. No visual seeding effect.

b. 1622. Some glaciation observable at the top of the central mass.

c. 1627. Definite glaciation at cloud top.

d. 1632. Glaciation, and some virga starting down.

e. 1634. The area extends.

f. 1639. Virga descends more.

g. 1643. The seeded area is large but starting to fuzz out.

h. 1649. The effect is dying away.

Fig. K-1. VISUAL EFFECT OF THE 29 JULY SEEDING (THE AIRBORNE GENERATOR WAS ON 1602:40-1628:05 LST).

or igniter malfunction the Alectos could not be set off, and so at 1602:40 one Fuquay generator was started. It remained on until 1628:05, and all the time the Cessna circled about in the same area centered 11 miles WNW of Control, staying as much as possible in good upcurrents under solid clouds at altitudes estimated between 15,000 feet and 17,000 feet.

The results of the seeding are apparent in Fig. K-1, showing the visual effects as observed from Control, and Fig. K-2, photographs of the M-33 10-cm scope. The cloud mass top glaciated, and later virga descended but never reached the ground. The seeded area size reached 3 miles across at 1640. The seeding was first observed by the aircraft and by radar about 18 minutes after the seeding started.

From the continuous sampler records, to be discussed later, an estimate of the number of crystals in the top core of the seeded cloud gave an average of about 3/cm^3 and peak concentrations of 10 to 20/cm^3. These values are just slightly smaller than those found by Todd (1964a) for a similar seeding operation the previous summer.

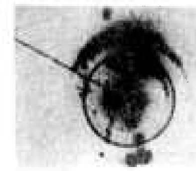
Aircraft Observations

The research Apache was flown in a brief spiral through a cloud base on the way up. Cloud base was 17,550 feet, -7.5C, and the lift in it was weak. Droplets several hundred feet above the base were mostly 7 to 10 μ diameter, with a few of 5 μ (some of 5 μ were found at all altitudes investigated). Some light aircraft charge was picked up in the cloud.

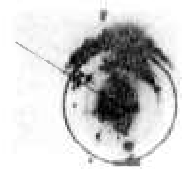
The Apache then ascended outside the clouds to an altitude just above the cloud layer. It made one brief pass through a top at 20,200 feet at 1607, getting light turbulence and a small charge on the airplane, and then waited above clouds at 20,900 feet. At 1619-1/2 the aircraft dipped through the seeded cell top (which could be seen to be glaciated) at 20,300 feet, and 2-1/2 minutes later went through an unseeded cell for comparison at 20,200 feet. These two penetrations will now be described in more detail.

In the unseeded cell, which was entirely water, the temperature reached -13C, which is right along the saturated pseudoadiabat from the cloud base observations. This core was as much as 4.7C cooler than the ambient air, the ambient air here being just above the inversion. There was a fairly strong downcurrent in the cell, a result of its strong negative buoyancy through the inversion. Turbulence was light and the temperature profile was rather smooth. In the seeded

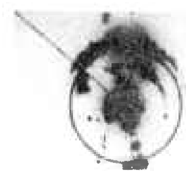
a. 1620-1/2. The radial line is the tracking radar azimuth going through the start of a barely visible echo at 11 miles just outside the circle of 10-mile radius. M-1 passed through the top of a seeded cloud 1 minute earlier, and is now located at the cross, almost on the circle. M-2 is the spot just N of M-1 and the echo.



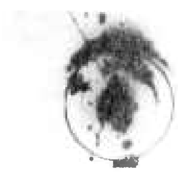
b. 1623. The echo has grown considerably, M-1 is just E of it, and M-2 is N of it. The circle radius has been expanded. All other echoes are from ground clutter.



c. 1628. M-1 has just passed over M-2, at the intersection of the circle and tracking radar azimuth. The seeded echo is getting more solid.



d. 1632. The seeding echo intensifies. M-1 is at the cross just E of the echo. M-2 is the dot on the azimuth line near the circle.



e. 1640. The aircraft are away from the seeded area. The echo has grown to a diameter of about 3 miles.

f. 1650. Just a trace of the seeding effect remains.

Fig. K-2. M-33 SCOPE SHOWING SEEDING ECHO AND AIRCRAFT, 29 JULY.

cell, which was entirely ice, the temperature averaged only 2C cooler than ambient, with a maximum of 3C cooler. The heat of fusion for the theoretical liquid water content at this altitude would only be about 1/4C. The observed greater warmth of the seeded core perhaps was due to the greater mixing in the seeded case; the turbulence was stronger, and the temperature variability greater than the unseeded case. There was a weak downcurrent in the seeded cell.

The droplet diameters in the unseeded case were 4 to 18 μ, and it was estimated that the "average mass" diameter was 11 μ. The concentration was about 900/cm^3. The liquid water content from the droplet sampler thus comes out comparable to the 0.72 gms/m^3 which theory gives for a cloud rise to 20,200 feet from a base at 17,550 feet and -7.5C. It should be emphasized that the sampler calibration is not precise and the number of frames counted was not large, and so the accuracy of liquid water content derived from the sampler is not great. The apparent agreement with the theoretical liquid water content serves mainly to suggest that the calibrations used in interpreting the sampler information are not unrealistic.

The crystals in the seeded cell were mostly hexagonal plates (as would be expected at these growth temperatures), some as large as 180 μ. Some of the plates showed ribbing of hexagonal structure. There were some triangles and many small irregular forms. Some clusters of crystals were probably present, but these were hard to identify with assurance because they break upon impact. There were no liquid droplets in the seeded cell.

During the traverse through the seeded cloud there was strong aircraft charging and some small vertical potential gradient. In the unseeded cloud there was only one-third of the gradient and likewise a much smaller aircraft charge. The numerical values have not yet been calculated from the data. It is not impossible that the apparent electrification arose primarily from triboelectric effects of the crystals on the aircraft.

The aircraft spiraled down after these traverses and flew in the subcloud virga. At 14,500 feet the observer noted that the virga was tiny drops of about 1/3 mm diameter, which are presumed to have derived from small clusters of crystals which had melted. There were no electrical effects there. The virga did not carry much below this point.

Comments on the Seeding

The seeded cloud was traversed 18 minutes after the start of seeding, and ice crystals up to 180 μ diameter were found but most were smaller. Considering that at least 10 minutes had elapsed with the crystals growing at temperatures colder than -9C, the crystals would have been larger if they had been growing at water saturation. It

appears, both from the crystal concentrations and the crystal sizes, that the cloud was thoroughly oversecded, as would be expected from the diffusion of that many nuclei into it. The crystals were measured near the cloud top, and the turbulence was somewhat greater than in the unseeded cell. It is probable that the silver iodide was well distributed throughout this portion of the cloud. The amount of mixing with surrounding unseeded portions of the cloud is not known. On any reasonable basis of calculation the number of crystals per cm^3 seems just a bit low if estimated from the generator output. This could be partially due to the quick, complete glaciation of seeded air rising into the cloud, glaciation which would then inhibit the activation of additional nuclei made available as the parcel rose and cooled.

L. Quantitative Seeding Concepts

Introduction

The cloud physics program at Flagstaff has involved dry ice seeding from aircraft and AgI seeding from ground and air. The AgI seeding from the air has represented the primary technique, and so will be discussed in greatest detail here. The concepts are generally applicable to the other seeding techniques.

A cloud represents a large, complex, varying entity to try to seed in an effective manner. The location and concentration of nuclei must be considered as time varying quantities. The local concentration of seeding material depends initially on the dispersion provided in the aircraft wake and in the atmosphere; the material moves to general areas of the cloud as a function of the mean motions within the cloud; and the effective number of crystals depends strongly on temperature.

The various interrelated factors will be reviewed in this chapter. First the main factors will be summarized, and then later some will be examined in detail.

Summary of Factors

1. In the field at Flagstaff it has been noted that a) expected visual and radar effects would follow appropriate seeding of supercooled clouds (see Chapter M), b) the magnitude of some of the effects depends strongly on the activity of the convective cell under consideration, c) it has often been difficult to find a strong upcurrent under a growing cell for seeding, presumably in conditions where the major buoyancy is established at relatively high altitude, d) it has often been difficult to position the seeding aircraft in a spot which shows good time-continuity to the upcurrent, e) seeding with the short-time Alecto units provided by NOTS-China Lake makes localized seeded areas which are almost impossible for the research aircraft to find subsequently, although eventually visual or radar effects can be observed.

2. Some quantitative calculations of the dispersion of seeding material can be made conveniently with the theory of diffusion in the inertial subrange. Although the calculations are over-simplified, they serve to point out some of the main factors involved in seeding.

3. With seeding plumes released from an airplane, for short time intervals (say less than 10 minutes) the volume which is seeded is

virtually all overseeded except in strong turbulence or at warm temperatures for which the airborne generator is inefficient. Therefore, for a practical effect, within broad limits it does not matter how many nuclei are dispensed, for whatever the quantity, the seeded volume will be mostly overseeded.

4. Around the edges of an overseeded volume there will be a region of low nuclei concentration where ice crystals can grow to large size. However, before the growth of such crystals can take place, localized overseeding can occur there from a) creation of more crystals from the silver iodide particles as the air rises and cools, and b) mixing with adjacent high crystal concentration volumes as the seeded region diffuses outward. Because the concentration distribution from turbulent diffusion is not uniform, there is somewhat more "correctly seeded" volume than would be derived from simple diffusion theory.

5. Seeding a typical growing cell from below cloud with a single Alecto pyrotechnic device will cause seeding (primarily strong overseeding) of only about 3 per cent of the volume of air involved in the cell system. Continuous seeding with an airborne AgI generator from below cloud can affect on the order of 50 per cent of the volume of air in the cloud system, overseeding much of it.

6. For any practical seeding the atmospheric turbulence provides the dilution needed to avoid overseeding. Thus the material should be released at a time (or distance) appropriate to the type of seeding needed. Usually the seeding should be done at least 5 or 10 minutes before the desired crystal growth is manifested. Thus the seeding should be done several miles below the "action" part of the cloud, or even further away. Because of the transient nature and unpredictability of cumulus growth details, it is very difficult to dispense the nuclei in the volume of air which, many minutes later, will be the correct part of the cloud. Releases of material from the ground in convective conditions have an advantage in that the particles are in air with high potential temperature, air which has a high probability of subsequently being included in cumulus development; particles randomly released in the subcloud layer have only a small probability of entering convective cells.

7. Dry ice drops from an aircraft can establish a sheet of crystals (typically, locally overseeding, and only becoming of a concentration permitting reasonable crystal growth as the sheet spreads throughout the cloud). Reaching the right part of the cloud is difficult and time is required for diffusion to act to give gross effects. The final crystal concentrations in overseeding cases may be much higher for dry ice seeding than for AgI.

8. The above factors emphasize that:

a. Routine calculation of diffusion rate, as from the inertial subrange concept and from in-flight measurements of turbulence intensity by a turbulence indicator (or even from pilot estimates) is desirable when actually performing seeding.

b. Preplanning of seeding methods also involves similar considerations.

c. To maximize the chances for gross effects, the seeding should cover a period of time which exceeds the duration of the important development phase of the cell system. The seeding period should be initiated ahead of the cloud cell development phase in order to provide adequate diffusion.

d. Glaciation effects on buoyancy will require seeding typically exceeding 100 crystals per liter. Seeding for significant precipitation growth requires concentrations of around 1 per liter, and further requires that the volume into which the hydrometeor subsequently moves is not overseeded.

e. The strong tendency for silver iodide to exhibit increased crystal concentrations as the temperature reduces can inhibit some direct precipitation increases unless the cloud top temperature limit curtails the effect.

Diffusion Computations

When AgI particles are released from an airborne generator, they rather quickly spread throughout the aircraft wake because of the turbulence and vortex motions created by the airplane. Thereafter the spread of the cloud of particles depends primarily on atmospheric turbulence. A reasonable estimate of the cloud dimensions as a function of time can be made by utilizing the inertial subrange concept. As long as the cloud cross section dimensions are less than a few hundred meters, and as long as the cloud is not in a strongly shearing flow, the inertial subrange simplifications can be utilized and diffusion relations derived by dimensional analysis and simple reasoning. The resulting equations represent a decidedly simplified model of the real diffusion, but they do offer a usable computational approach to quantitative seeding considerations.

In the inertial subrange of eddy sizes (typically from 1 cm to beyond 100 meters in the atmosphere at heights exceeding several hundred meters), all statistical parameters can be uniquely related to ϵ, the steady state

rate of dissipation of turbulent energy into heat (see, for example, the review by MacCready, 1962a). Batchelor (1950, 1952) has derived the form of diffusion equation for the relative dispersion of particles in the inertial subrange. MacCready (1964a) has tried to come up with simplified consistent equations which agree with Batchelor's formulations and can be compared with experimental data; some of the following discussion can be found in greater detail in that reference.

The growth of an ensemble of point pairs, the spreading of a cloud puff, or the growth of a line wake of characteristic size Y, should all follow the following predictions: initially, at "short" times at which the initial size of the cloud is of concern, the growth of the cloud or partical variance should be in a (time)^2 regime ($\overline{Y^2} - \overline{Y_0^2} \sim \epsilon^{2/3}\overline{Y_0^2}^{1/3} t^2$), and later, at "intermediate" times at which the initial size is of importance but before the size bounds of the inertial subrange is reached, the growth should be in a (time)^3 regime ($\overline{Y^2} \sim \epsilon\, t^3$). The two regimes should merge at a time $t_1 \sim (\overline{Y_0^2}/\epsilon)^{1/3}$. Formally making the two regimes merge at t_1 and displacing the time reference in the (time)^3 regime slightly to permit this fit, yields consistent diffusion growth equations for the inertial subrange. In the "intermediate" period, the simplest single equation for cloud size which approximates the more exact equation is:

$$\sigma = \sigma_0 + C_7\ \epsilon^{1/2}\ t^{3/2} \qquad (1)$$

where σ represents the standard deviation of the plot of nuclei concentration as a function of radius from the cloud center, σ_0 is the initial size of the wake, C_7 is a dimensionless coefficient of order unity, ϵ is the equilibrium rate of dissipation of turbulent energy into heat, t is time with t = 0 at the time of release. In the early stages of the cloud growth the more exact formulas are more complex, and also the wake turbulence can contribute appreciably to the growth, but for the longer periods Equation (1) is a reasonable first approximation. Experimental data do show useful agreement with the (time)^3 regime, which is the (time)$^{3/2}$ relationship in Equation (1).

The value of the dimensionless constant of Equation (1) is not known, except that it should be of order unity. A value of 0.5 is suggested for use here with an expanding wake, from the following considerations. The value of the dimensionless coefficient for the size variance of an ensemble average of point pairs in the "short" (time)^2 period is found by comparison with Eulerian spectra to be 0.95; the value for the "intermediate" (time)^3 period is probably also not far from 1 for point pairs. For the expanding plume having dimensions referenced to σ (which will be

described more thoroughly later), a radial standard deviation of the concentration distribution, a dimension on the order of 2σ should correspond to the dominant size dimension, and so by analogy to the point pair case

$$(2\sigma)^2 = \overline{Y^2} \cong 1 \cdot \epsilon t^3 \tag{2}$$

Thus Equation (1), for an expanding plume, can be written as:

$$\sigma = \sigma_0 + 0.5 \epsilon^{1/2} t^{3/2} \tag{3}$$

The values of ϵ for different meteorological conditions have not yet been well established. Generalizing from the limited available data, MacCready (1964b) has suggested the following scale:

Negligible	$\epsilon < 0.22$ cm^2 sec^{-3}
Light	$0.22 < \epsilon < 3.0$
Moderate	$3.0 < \epsilon < 41.5$
Heavy	$41.5 < \epsilon < 543$
Extreme	$\epsilon > 543$

The descriptive terms are derived from pilot subjective reactions. The RMS values of typical vertical aircraft accelerations turn out to be proportional to $\epsilon^{1/3}$, for a fixed aircraft type, altitude, and air speed. The pilot labels should relate most directly to the aircraft accelerations, and thus show considerable scatter when related to the actual turbulence $\epsilon^{1/3}$ because of aircraft type, altitude, and speed variations as well as because of the subjectivity factor. In any case, for design and simple computational purposes, one can assume:

$\epsilon = 1$ cm^2 sec^{-3} as being representative of light turbulence
$\epsilon = 10$ cm^2 sec^{-3} as being representative of moderate turbulence
$\epsilon = 100$ cm^2 sec^{-3} as being representative of heavy turbulence

These values will be used here as representative ones for discussion purposes.

Neither theory nor experiment have yet established what sort of distribution function of particle concentration exists across the expanding wake. Since the exact distribution shape is relatively immaterial in the consequences of the numerical computations, and since the exact value of C_7 is unknown and thus certainly represents some numerical error, the distribution which is chosen is that which makes the computations simplest. It is assumed that a plot of concentration vs. radius forms a half of the standard error function curve.

Thus

$$n = \frac{A}{\sigma\sqrt{2\pi}} \; e^{-\frac{1}{2}\frac{r^2}{\sigma^2}} \qquad (4)$$

where n is concentration in nuclei/cc, A is a scale factor which will be evaluated later, and r is the radius at the point in question. By standard Gaussian distribution relationships,

$$\int_0^\infty n\, dr = \frac{A}{2\sqrt{2\sigma}} \qquad (5)$$

The total number of crystals, N, in a 1 cm cross section slice of the plume is related to A by noting:

$$N = \int_0^\infty 2\pi r\, n\, dr = \frac{\sqrt{2\pi}\, A}{\sigma} \int_0^\infty r\; e^{-\frac{r^2}{2\sigma^2}}\, dr = A\,\sigma\sqrt{2\pi} \qquad (6)$$

Thus at any radius,

$$n = \frac{N}{\sigma^2\; 2\pi} \; e^{-\frac{1}{2}\frac{r^2}{\sigma^2}} \qquad (7)$$

and, by combining Equations (3) and (7), n is given as a function of N, t, and r.

Some consequences of these calculations are given in the following four figures. Figure L-1 is a plot of σ vs. t for three values of ϵ (ϵ = 1, 10, and 100 $cm^2\, sec^{-3}$). Figure L-2 is a plot of n vs. r for various σ, assuming a particular value for N (namely, $N = 10^{11}$ nuclei/cm of flight path, corresponding to a generator output of $5 \cdot 10^{14}$ particles/sec and a flight speed of 50 m/sec). This is a realistic output value from the type of Fuquay-Skyfire airborne generator used (Fuquay and Baughman, 1962). The value of N at warmer temperatures is also given on Fig. L-2, arising from Fuquay and Wells (1957) and Fletcher (1959). Figure L-3 is a crossplot of the first two figures, and shows the evolution of concentration levels for a particular source strength ($5 \cdot 10^{12}$ nuclei/sec, referring to the effectiveness at -9C, and so $N = 10^9$ nuclei/cm of flight path) and a particular low turbulence level (ϵ = 1 $cm^2\, sec^{-3}$). For -13C the concentrations would be increased 10-fold, and at -20C 100-fold. For greater turbulence, the concentration situation would be reached more quickly. Figure L-4 shows diagrammatically the growth and movement of the silver iodide cloud above a seeding aircraft. This figure was derived considering ϵ to be 1 $cm^2\, sec^{-3}$

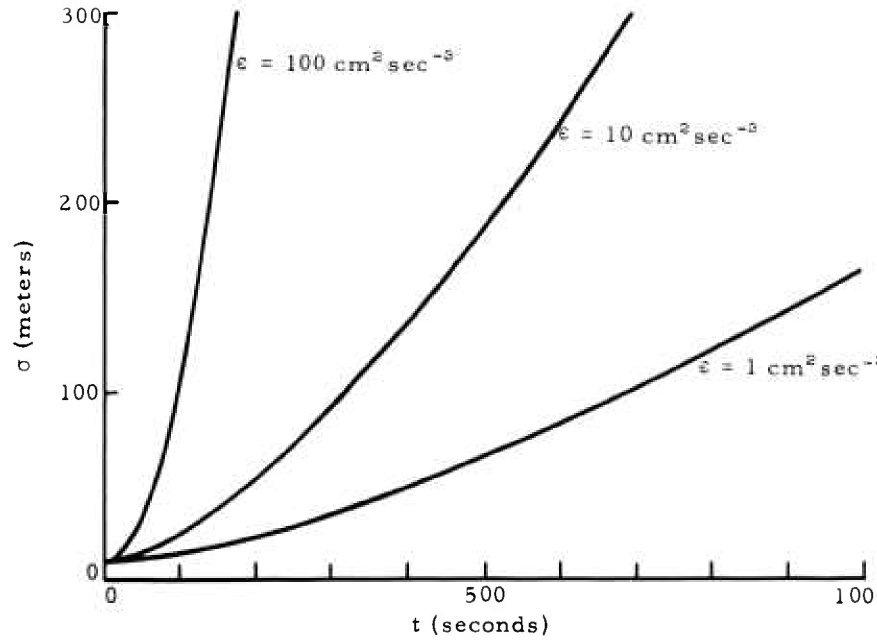


Fig. L-1. GROWTH OF AIRCRAFT PLUME DIMENSIONS AT VARIOUS TURBULENCE INTENSITIES.

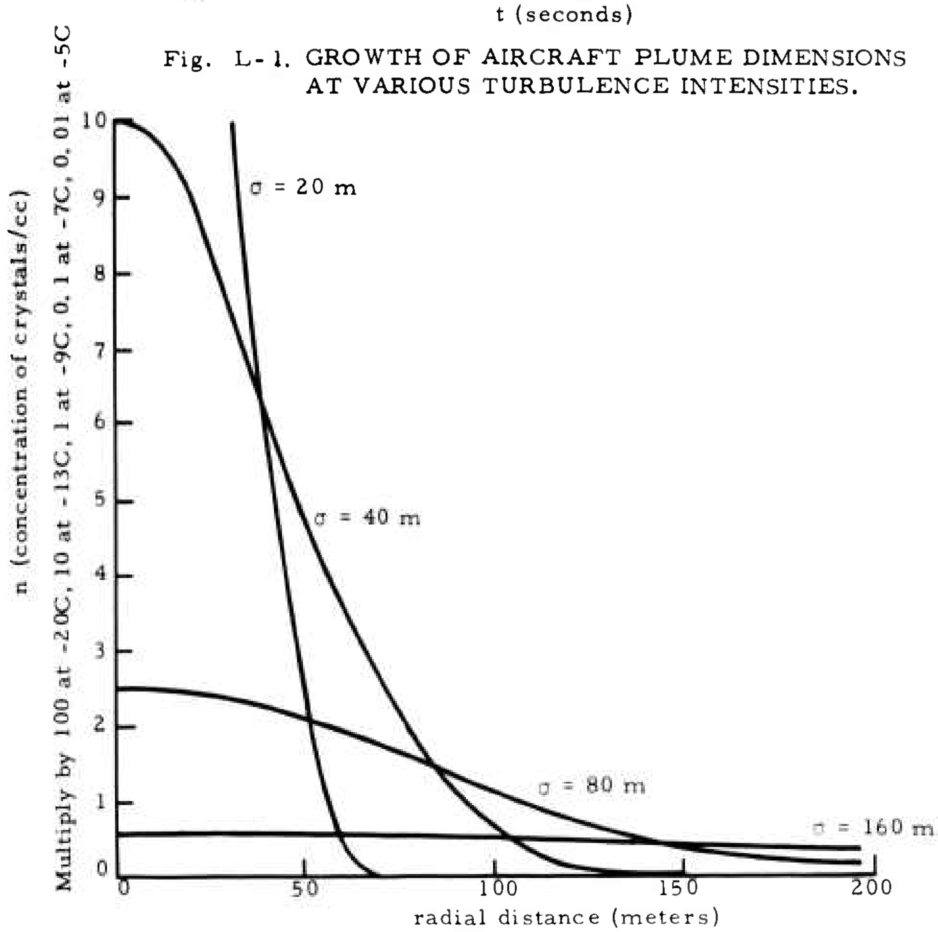


Fig. L-2. CONCENTRATION VERSUS DISTANCE IN AN EXPANDING CLOUD.

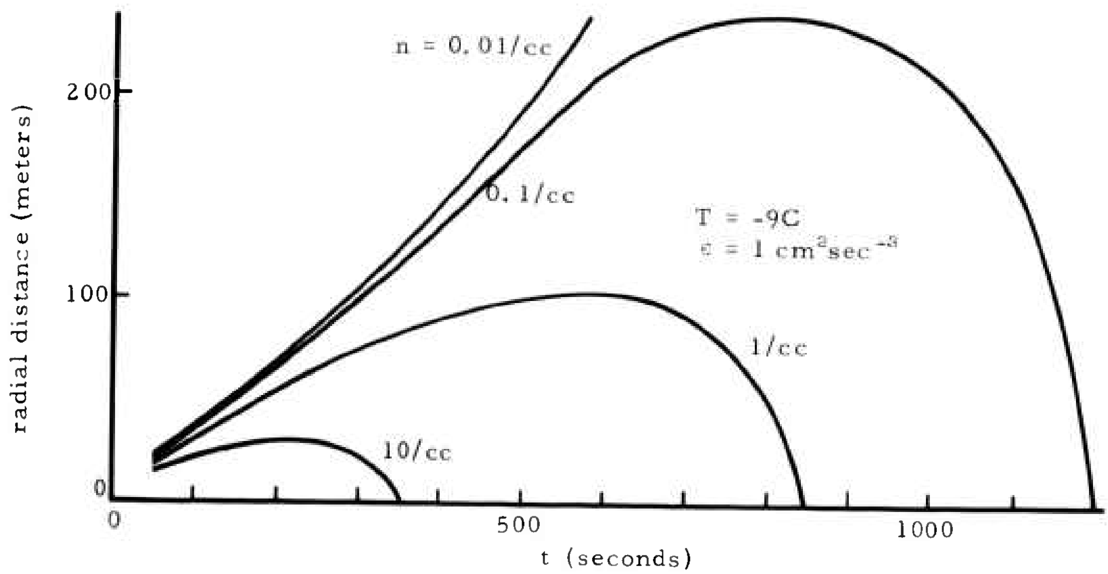


Fig. L.-3. CONCENTRATION LEVELS AS A FUNCTION OF TIME AND DISTANCE FOR T = -9C AND ϵ = 1 cm^{2}sec^{-3}.

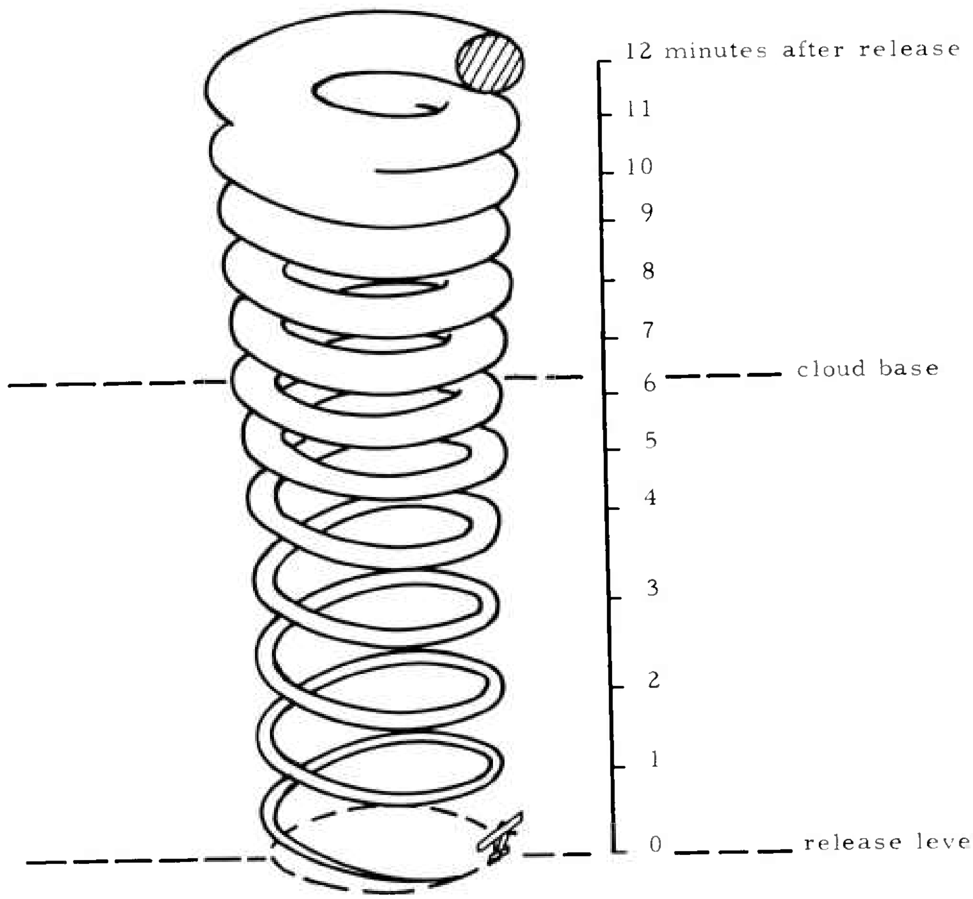


Fig. L-4. IDEALIZED DIAGRAM OF THE MOVEMENT AND EXPANSION OF A AgI PLUME IN LIGHT TURBULENCE CONDITIONS FROM AN AIRCRAFT SPIRALING AT A CONSTANT LEVEL IN AN UPCURRENT (FROM TODD, 1963).

A 45-second release, representing the effect of a single Alecto unit, would be represented by 3/4 of one turn.

and taking the size dimension to be diameter, about 2σ. The figure was found to be reasonably consistent with the distribution of ice crystals from seeding as picked up by the continuous sampler. In the very cores of large convective clouds the turbulence level is often light to moderate, not strong, although at the upcurrent edges and top the turbulence will be more severe.

Comments

From the four figures the dominant features of the diffusion from an airplane AgI generator can be surmised. Figure L-3 shows how a particular point in the air (at $T = -9C$, $\epsilon = 1\ cm^3 sec^{-3}$), say at a distance of 100 meters from the wake center, is initially unseeded, then very quickly from 250 seconds to 300 seconds jumps to 0.1/cc, is 1/cc at about 500-600 seconds, and only decreases below 0.1/cc after 1150 seconds. At any given radial distance or turbulence level the effect is similar; first an increase, then a decrease in concentration. These curves are all derived from simple theory and it is recognized that the movement of particles is much more complex than the curves show. In particular, the curves refer to the average concentrations, while in practice the concentrations at a particular radius will show fluctuations and have adjacent small unseeded and overseeded air parcels. However, the distribution of small turbulent eddies is surprising uniform and after a short time the particles in the volume will "smooth out" (as for example in a smoke plume virtually no volume is free from some smoke.

The same sort of reasoning can be applied to the spreading out of crystals from dry ice seeding by dropping pellets through the supercooled cloud. The number of crystals which can be derived from a falling pellet has not been established as yet with the needed accuracy; the estimates, from theory and from experimental evidence, vary from 10^{10} to 10^{17} crystals per gram of CO_2. Eadie and Mee (1963) found about 10^8 crystals per meter of fall, with the number of crystals decreasing rapidly at temperatures above -7. From all the evidence, CO_2 pellets probably produce only 10^{-5} to 10^{-3} as many crystals per gram as AgI does per gram in a cloud at -20C; however, many more grams of dry ice are used in typical seeding than grams of AgI. The pellets, because of their fall, can be dropped through the cloud to form immediately a sheet of localized glaciation which may have desired cloud dynamics effects. Compared to silver iodide particle release from an airplane, the dropping of CO_2 pellets initially distributes the crystals rapidly over a large area. Localized overseeding will still occur, but can be more rapidly overcome by turbulent diffusion.

The Fuquay type airborne generator apparently produces about $5 \cdot 10^{14}$ particles per second, active at -20C, consuming about 0.15 gms of AgI per second. Fuquay (private communication) finds the same total output.with comparable numbers at other temperatures, can be obtained with the same generator using less silver iodide by a factor of 5 or so. By using multiple burner heads and two generators per aircraft, over 10^{15} particles per second at -20C is attainable.

The NOTS Alecto units consume about 1200 grams of silver iodate in the 45 seconds burning time, 27 grams per second, about 200 times the rate of the standard Fuquay generator. A somewhat lower efficiency is assumed for the pyrotechnic Alecto devices, giving them an output of $2 \cdot 10^{15}$ particles per second active at -20C.

The concentration calculations in this chapter assume the diffusion arises primarily from the atmospheric turbulence. For ϵ considerably less than 1 $cm^2 sec^{-3}$ (which is not common in seeding circumstances) the aircraft wake can constitute the main diffusing power for the spread of the cloud even after 10 or 20 minutes. The heat of fusion liberated by seeding a supercooled cloud can also quickly manifest itself in cloud motions and turbulence. However, the heating is rather small except for the high liquid water contents which are obtainable only in cumuloform clouds (heating is on the order of 1/3°C for each 1 gm/m^3 of supercooled liquid water content), and so this source of turbulence should be relatively unimportant compared to atmospheric turbulence.

Overseeding by Dry Ice Versus Silver Iodide

The MRI report on the 1962 Flagstaff project noted (page 34) that ice crystal concentrations of 20 to 100 cm^3 and $500/cm^3$ were encountered in clouds seeded by dry ice. Clouds seeded by silver iodide had 1 to $3/cm^3$ and 10 to $20/cm^3$.(the latter figure corrected to 50/cc by Todd, 1964a). In the 1963 season, as noted in Chapter M of this report, average concentrations of $3/cm^3$ and peak concentrations of 10 to $20/cm^3$ were encountered in a cloud seeded by silver iodide. All of these concentrations can represent complete glaciation in Flagstaff cumulus clouds.

There seem to be several reasons for the difference in crystal concentration from the two types of seeding. The dry ice seeding does create crystals within the cloud, and so the number observed later per cm^3 will be a function of how the drystals diffuse. The silver iodide operation only involves providing nuclei at a distant point; these nuclei move to the pertinent cloud volume, and then the cloud can create crystals. Thus typically the diffusion limits the crystals from silver iodide to about $50/cm^3$ (see Todd, 1964a, and Chapter M of this report)

for medium-cold portions of a cloud seeded from a good distance below. An additional limitation can arise because the initial crystals may completely overseed the seeded volume and maintain it near ice saturation as more water vapor is made available from a) mixing with adjacent volumes, and b) rising and cooling. Thus the additional nuclei available later as the parcel rises might not be able to grow in competition with the existing large crystals. The exact limit of crystal numbers by this possible competition effect is difficult to calculate inasmuch as it depends on temperature, upcurrent strength, and unknown details of turbulent mixing of unglaciated cloud air into the plume. If all the air rising into a cloud is thoroughly and evenly saturated with silver iodide, then only small crystal concentrations seem likely for a cloud base at -9C, say, and an upcurrent of 4 m/sec. Assume 3 crystals/cm^3 are available at -9C, meaning later 30/cm^3 at -13C and 300/cm^3 at -20C will be available in the same air volume. From the plot on crystal growth versus time and temperature for water saturation given by Todd (1964c) it appears that the first 3 crystals/cm^3 are just on the borderline of being able to keep the cloud essentially glaciated at temperatures below -10C.

The above discussion contains a suggestion of the value of being able to produce silver iodide particles which nucleate at warm temperatures without simultaneously producing many more particles capable of nucleation at colder temperatures. As shown by MacCready (1959), these latter nuclei can often interfere with the scarcer ones which would otherwise be capable of generating useful precipitation.

The seeding methods studied here seem quantitatively able to produce substantial overseeding, and of course any smaller amount of seeding. Complete glaciation is possible, with all the crystals being small, and "complete overseeding" is easier to attain (defined as enough glaciation to prevent hydrometeors from growing enough to fall through the updraft).

It is emphasized here that the efficiency of seeding must be viewed as a function both of the local concentration of crystals and of the total volume having the particular concentrations. The nuclei or crystals must somehow be spread appropriately. For the convective clouds studied here, the material should spread throughout the upcurrent core. Silver iodide released at the aircraft, as from the acetone generator or the Alecto pyrotechnic, is thus dispensed at low altitude so as to give as much time as possible for the turbulence to spread the particles. Dry ice is dropped through the cloud, but the 0C isotherm limits the origin of crystals. Pyrotechnic devices moving vertically through the upcurrent, to create nuclei over a great vertical depth even including the region far below the cloud, should be effective for some operational seeding.

M. Observation of Seeding Effects

Introduction

This section will review some of the effects seeding can produce and will discuss the observation of these effects. The discussion here is limited to qualitative descriptions. Some case studies are presented in the 1962 season final report, in Part A of the 1963 season final report, and in Chapter M of this report, and quantitative considerations are given in Chapter L. The effects discussed are 1) visual signs of glaciation, 2) radar echoes, 3) precipitation falling from cloud base, 4) increased convective activity, or equivalently, increased temperature excesses over the environment in the part of the cloud converted to ice. The development of ice hydrometeors within the cloud is equivalent to 2) and 3), since the seeding as performed can only involve ice hydrometeors. Less direct effects, such as decreased convection from the shielding of the sun by seeding-created cirrus shields, or downcurrents and cloud decay from precipitation effects, are not treated here.

Some effects are easy to observe, visually and on radar. There are quite a few marginal days at Flagstaff when the natural clouds are supercooled but not cold enough to activate appreciable numbers of natural nuclei. Then any glaciation or precipitation unquestionably comes from seeding. Good examples of this are the seeding of 26 August 1958, reported by MacCready (1961), and the seeding of 29 July shown here in Chapter K. The more important situations arise when natural clouds are already producing echoes. In some cases seeding effects can still definitely be observed, but as the weather situation gets stronger the opportunity to produce distinct effects grows smaller even though the effects of seeding can sometimes be large. In such cases the quantitative physical interpretation of events becomes important in analyzing a seeding effect. A comparison of measurements in a nearby (in time or location) similar unseeded cloud helps, but sometimes even this aid is unavailable.

Visual Observations of Glaciation Due to Seeding

On some days there is no visible natural glaciation, in which case it may be quite easy to identify seeded areas if they are producing glaciation. Typically natural glaciation from cumulus cloud tops is an important visual phenomenon at -25C or colder, although at Flagstaff it sometimes appears at -10C and warmer. Glaciation by dropping dry ice from an aircraft can be achieved at -5C or maybe even -4C. Glaciation by AgI seeding can occur quite rapidly and spectacularly at -12C to -15C, and more slowly at temperatures presumably as warm at -4C. Even

very simple estimates of height and temperature are sufficient to distinguish which glaciation is natural and which is seeded, on many days when both occur.

In the 1962-1963 program, seventeen events of distinct glaciation from seeding were observed; five from dry ice, one with an Alecto, and the rest from the acetone silver iodide generator. These cases are when the only observed effect was glaciation. The appearance of glaciation from seeding also occurred in many other cases when radar echoes, virga, and precipitation developed.

Radar Echoes Due to Seeding

Under some conditions the first radar echoes in natural clouds appear at a characteristic height, and seeded first echoes can be made to appear substantially lower. Sometimes it is possible to predict the appearance of the first radar echo from the development of the visual cloud, using criteria relating to how long it takes after a cloud top has passed a critical height. On days at Flagstaff when there are isolated cumulonimbus clouds and the sky is not extensively glaciated the natural echoes typically appear at 26,000 ft. Seeding a cloud with dry ice as it passes -10C at about 20,000 ft usually produces echoes in 4 to 6 minutes at about 22,000 ft, about -15C. When clouds are seeded which do not exceed -10C it takes about 12 to 15 minutes to get radar echoes, a time which tends to be long compared to the life of the active part of the upcurrent. If the clouds had slower convection and slower dilution rates, then it might be possible to obtain substantial echoes at lower elevations.

During the last two seasons, there were fourteen fairly distinct cases of a radar echo due to the seeding; four from dry ice, the others from the acetone silver iodide generator.

Precipitation Due to Seeding

The requirement for any substantial precipitation is that it fall back through a cloud. In convective clouds this means that seeding must grow the hydrometeor to a size where it has a fall velocity greater than the updraft rate before it is shed out of the top of the cloud. This means that clouds with slow updraft rates and substantial heights favor precipitation. The critical relationships of seeding temperature, updraft rate and height that favor precipitation have not been worked out yet, but could be derived with some confidence from existing theory. There are of course other factors that enter in too, such as the cloud liquid water content.

For 1962 and 1963 it is felt that precipitation or substantial virga can be attributed to the seeding in eighteen cases; three with dry ice, three with Alectos, and the rest with the acetone generator. Many of these of course also showed distinct glaciation.

In 1962 and 1963, on five additional days as well as many of the above days, ice hydrometeors were found by the observation aircraft in seeded clouds only or in seeded clouds at lower altitudes than nearby natural clouds.

Increase in Convective Activity Due to Change to Solid Phase

Changing a cloud from liquid phase to solid phase by seeding causes an increase in buoyancy proportional to the liquid water content of the cloud at the time the change starts. In the Flagstaff area the typical liquid water contents permit a maximum increase in temperature due to the heat of fusion on the order of 1C, while in the tropics this can exceed 2C. Woodley (1964) has made a study with Flagstaff data in an effort to find out how frequently the expected increase in buoyancy might be capable of producing an important increase in the height of convection.

The study utilized a very simplified model of the process, but still it is felt that the implication of the results is generally valid. The study showed that there was considerable opportunity for seeding to increase the height of convection, very often above 5000 ft; sometimes even beyond 15, 000 ft, because frequently convection was limited by only slight stability. The study also suggested that the limit of convection was controlled by several factors that had large variations with respect to the resolution of observation. One of these factors would be the limiting environment stability at the cloud top. This would be expected to vary with the ascending or descending motions of the air at that level. Waves over the mountain or over the whole plateau system and convective wake phenomena could effect this critically as well as could the compensating motions about well developed cloud systems. Another factor is that the ultimate height of convection is critically dependent upon the temperature and moisture flowing in at cloud base. This would be expected to vary the cloud buoyancies by as much or more than the effect of the seeding. This variation would depend upon whether the air feeding the cloud came from the forested area or desert areas, as well as how it was effected by the solar angle of the various slopes that it passed over. For these reasons it is expected that, on almost any day over land when seeding can overcome the stability that is limiting convection, some of the natural clouds even without glaciation may overcome this limit too. This would indicate that more of the clouds could overcome the stability if they were

seeded, or that the first clouds over the peaks might be made to develop taller sooner with seeding. The problem to establish that seeding is the cause of increased convection in this area is in general not simple. Presumably the ideal location for verifying this seeding effect would be over tropical oceans where the moisture content of clouds is maximum and the surface conditions are relatively uniform compared with the effect expected from seeding.

Nevertheless, at Flagstaff seeding appears frequently to be followed by some increases in convective development, and occasionally by substantial increases. The problem of verifying these with definitive observations is difficult. Case studies in the 1962 report give measurements of increased buoyancy in a seeded cloud and a suspected top growth from seeding, and Woodley (1964) cites these and other cases. In 1962 and 1963, seven events suggest added convective motions due to seeding; one with dry ice, two with Alectos, and four with the acetone generator. Often also the seeding will produce distinctive "fingers" of glaciated cloud pushing up through the cloud top, observed by D. M. Fuquay (private communication) at Flagstaff and Montana.

Icing

As would be expected, the icing on the observation aircraft rising in a seeded cell appeared to the observer to be different from that accruing in equivalent conditions in other cells. The observers description would usually be that the icing was not present at all or was very light and feathery.

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OVER-ALL CONCLUSIONS

The abstract and the separate chapters present the substantive conclusions of the project, and these detailed results will not be duplicated here.

The project aim has been to gain significant understanding of the physical mechanisms which go toward causing the development of convective clouds, and their flow fields, precipitation, and lightning. Even in the relatively simple outdoor cloud laboratory at Flagstaff the interrelations between all these factors are extremely complex. Individual problems can be studied somewhat separately, but the secrets to the dominant factors can only be uncovered by paying attention to the whole cloud dynamics - cloud microphysics system. Thus the project aims necessitate a broad program, involving an extensive ground and air data acquisition capability and, even more vital, a data processing and analysis capability that can flexibly handle the details comprising the complex meteorological situation. The techniques developed and employed for the outdoor cloud laboratory at Flagstaff have worked effectively and have permitted the project aim to be realized.

In the 1963 season important particular results are:

a) The seeding effects which have been noted and measured are in reasonable agreement with the effects which are to be expected by quantitative consideration of the techniques of seeding and the cloud microphysics and dynamics.

b) Precipitation mechanisms at Flagstaff cover those found elsewhere. Hydrometeor growth in some clouds is exclusively in the ice phase (and the natural nuclei concentrations show large variations), in other clouds it arises from giant nuclei in a "warm" cloud process, and also rapid freezing of large drops can occur.

c) The convective wake behind the isolated peaks has been further evaluated and related to the physical parameters causing it. A spectrum of wave effects is observed in the lee of the peaks.

RECOMMENDATIONS

Some detailed recommendations have already been presented in preceding chapters. Every separate subject treated has brought up several new questions for each answer that has been obtained, and research could profitably be pursued in every subject. Only the overall recommendations will be given here.

The data already collected in five seasons at Flagstaff constitute a unique library of information which is becoming increasingly useful as knowledge in the cloud physics field increases. Of special interest are the 1963 season records on electrification, precipitation mechanisms, and seeding effects in complex cases; these records have only been treated in a brief way in this report. Further analysis is very desirable, and is particularly economical compared to obtaining new data.

The measurement principles in use in the final field season, and the data reduction and analysis methods applied to them, have handled their tasks in a reasonable manner. The techniques developed around the ideal Flagstaff outdoor cloud laboratory can profitably be applied to specific projects at other areas as well as at Flagstaff.

For some critical studies the instrumented aircraft by itself can yield definitive answers. Therefore it is suggested that a mobile version of the Flagstaff measurement system be developed consisting of the instrumented airplane with a minimum ground system of even just a time lapse camera, and used at representative locations to obtain comparison data on precipitation mechanisms and on electrification. It would always be desirable to phase the operations into existing cloud physics and seeding programs having radars and ground networks, but valuable results are obtainable even with the airplane alone. As demonstrated here, the airplane system can resolve the critical factors of the precipitation mechanism: the existence of giant nuclei, the evolution of the cloud droplet spectrum as air rises in the convective column, the coalescence rate of cloud droplets, the initiation of ice crystals from natural and artificial effects, the development of hydrometeors, the freezing of large droplets at warm temperatures, and related electrification factors, and also grosser features such as the liquid water content distribution, buoyancy, the upcurrent dimensions and evolution, and the environment situations. An aircraft like the single engined and twin engined ones used at Flagstaff would suffice, but a better choice would be one easily capable of altitudes up to about 33,000 ft. The aircraft should be big enough for the instrumentation, but still light enough to fly slowly and perform

spirals in upcurrent cells, and simple enough for easy maintenance at remote sites. Instruments of the type used at Flagstaff are adequate, proving more attention is paid to deicing for wetter conditions, and that there is a long period of shakedown and calibration before the field seasons. The experience and motivation of the flight crew is as important as any other factor.

At Flagstaff, the convective wake represents a unique opportunity to establish quantitative effects from seeding in fairly large convective cells and storms. On good days the phenomenon is persistent. It appears to be rather predictable, and will certainly become more so as future studies are made. Thus seeding and control investigations can be performed on different days or on different portions of the same day. Some trials could be directed at strong overseeding to prevent precipitation and perhaps electrification, some could involve lesser seeding to create cloud dynamics effects without completely wiping out hydrometeor growth, and some could be just for precipitation increasing or initiation. As pointed out in the discussion on quantitative seeding, ground generators might prove to be particularly effective in seeding this situation.

Quantitative or engineering paper studies of seeding methods are warranted now, since initial considerations appear to be yielding results consistent with what actually happens in the field, and since the basic cloud physics and cloud dynamics data are available in the literature for more exhaustive treatment. The practical development of silver iodide generator technology could also fruitfully be emphasized, with the aim of increasing the nuclei available active at warm temperatures while not increasing (and preferably decreasing) the numbers which will be activated at colder temperatures.

PERSONNEL

Personnel are listed here who devoted more than two weeks of time to the conduct of program.

Field Program

The following MRI personnel participated in the work at Flagstaff:

Dr. P. B. MacCready, Jr.	Project Director
Dr. T. B. Smith	Project Scientist
Mr. C. J. Todd	Project Scientist - Operations Director
Mr. K. M. Beesmer	Data Supervisor
Mr. D. Smith	Data Assistant
Miss E. Woodward	Calibration & Flight Observations
Mr. F. Clark	Radar Systems
Mr. J. Gretta	Aircraft Systems & Pilot
Mr. E. Hindman	Drop Sampler
Mr. R. Williamson	Drop Sampler
Mr. R. Day	Pilot
Dr. C. W. Chien	Analysis
Mr. N. Johnson	Electronics Technician
Mr. M. Pate	Radar Assistant
Mr. W. Woodley	Data Assistant
Mr. R. Beesmer	Instrumentation

MRI hired the following personnel at Flagstaff for the project:

Mrs. Marjorie Driscoll	Local Office Coordinator
Mr. Robert Schley	Photographic recording
Mr. D. Jones	Communications
Mr. Bill Adams	General helper

Mr. Larry Davis, of Pennsylvania State College, served as a consultant at the start of the field work in connection with optimizing the usefulness of the M-33 radar. Mr. Alexander Proudfit participated in the field work as instrument specialist and aircraft observer under sponsorship of the National Science Foundation, Grant No. G11969 to the Atmospheric Research Group.

Dr. V. J. Schaefer, in addition to assisting the program in his consulting capacity to MRI-ARG, organized and handled eight student trainees from the Atmospheric Sciences Center of New York State University, with support from the National Science Foundation. These students assisted the MRI-USAERDL program on a part-time basis. The students were:

- Ronald Bidula
- Stephen D. Clark
- Don J. Cramer
- John A. Jaros
- Garland Lala (Asst. Director)
- Alexis Long
- Francis Nicholson
- Eugene Wengert

Preparations for the Field Program

The instrumentation development and general project planning involved most of the MRI personnel who are listed above, plus the following who handled machining, electronic development, and coordination:

- Mr. J. Bennett
- Mr. D. Chin
- Mrs. C. Clarke
- Mr. C. Eudaily
- Mr. A. Frost
- Mr. D. Sanders
- Mr. R. Sloane
- Mr. Vanevenhoven

Analysis and Research Program

The responsibilities for the various separate research projects have been listed previously in the Introduction of the Discussion. The initial data reduction was handled under C. J. Todd, by D. Smith, K. Beesmer, C. W. Chien, and E. Hindman. The analyses were performed primarily by P. B. MacCready, C. J. Todd, T. B. Smith, A. Weinstein, and C. W. Chien.

Meteorology Research, Inc., Altadena, Calif.
STUDY AND MODIFICATION OF CONVECTIVE STORMS.
P.B. MacCready, Jr., T.B. Smith, C.J. Todd, and A. Weinstein
Report No. 4B. 1 April 1963 - 31 March 1964. 128 p.
incl. illus. tables photographs (Rept. No. MRI64 FR-144)
(Contract DA 36-039 SC-89066, Proj. No. 3A99-27-005-06)
(ARPA Order No. 265-62) Unclassified report.

This report describes instrumentation, analysis techniques, and research results from the 1963 field season of a basic investigation of cloud physics and cloud dynamics at Flagstaff, Arizona. Radar, instrumented aircraft, and cameras were used to measure the dominant factors pertaining to seeded and unseeded cumulus clouds. Results include: a) The cause of the persistent convective wake and associated precipitation found downwind of the peaks was further analyzed, and its position related to wind speed. b) The wave motions downwind of the peaks were found to be somewhat analogous to the motions behind two-dimensional ridges. The waves are apparently not of primary importance in the development of the convective wake. c) Two distinct types of radar angel echoes appeared on the 10 cm radar during warm, dry, light wind conditions; some moving with the wind and related to conventional thermals, the others moving unrelated to the wind. d) The continuous particle sampler was used with corrections to give quantitative droplet spectra which showed rapid coalescence of droplets even smaller than 10 microns diameter. A technique evolved for finding the presence of large droplets on the sampler film. e) On one occasion giant droplets were found entering cloud base and initiating liquid drops. Some of the drops subsequently froze before -6C while rising in the upcurrent. f) Undiluted cores, typically of 1 km dimensions, were found even up to the highest altitudes sampled, 9000 ft above cloud base. g) Substantial outward lateral velocities were encountered during penetrations of cells. h) Qualitative results of cloud seeding for two seasons are summarized, and quantitative theory developed for aircraft seeding which is consistent with observed effects. The atmospheric diffusion is usually found insufficient for avoiding localized overseeding for aircraft generators.

UNCLASSIFIED

1. Clouds-Physical properties.
2. Clouds-Electrical properties.
3. Cumulus clouds-Growth.

I. Title: Project Baton
II. MacCready, P.B., Jr.
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